SURVEY OF THE POTENTIAL OF PLASMA TECHNOLOGY APPLICATION IN CANADA

FINAL REPORT

BY

THE TECHNICAL DEVELOPMENT DEPARTMENT
SNC INC.

FOR

CANMET, ENERGY, MINES AND RESOURCES, CANADA

The SNC Group

November, 1985
Montréal

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SNC INC.

PRINCIPAL INVESTIGATOR

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ABSTRACT

The study was carried out by the Technical Development Department, SNC Inc., for the Canada Centre of Mineral and Energy Technology, CANMET, Energy, Mines and Resources Canada. The study comprises an assessment of the potential of plasma technology application in several Canadian industrial sectors and processes including iron and steel production, conversion of hydrocarbons to chemical and synthetic fuels, melting-remelting operations, production of refractory metals and alloys, synthesis of extra-pure, equiaxed, fine particles for production of advanced (engineering) ceramics.

The study is limited to currently available plasma technology and processes which have been demonstrated either commercially or on a pilot-plant level, or during extensive laboratory investigations. Chapter 7, "Potential of plasma application in production of advanced ceramic materials", is based, as an exception, on information of relatively small-scale laboratory investigations available in the public domain.

A brief description of the currently available plasma technology (generators, reactors, processes and systems) is given to allow comparison with corresponding conventional or competing processes, where applicable. Technical assessment of the potential of this plasma technology application in Canada and R&D strategy to support the technology commercialization are presented. Also, where possible, an attempt has been made to include some preliminary economic considerations.

SUMMARY OF CONCLUSIONS, AND RECOMMENDATIONS

A review of currently available plasma technology and an assessment of the potential of the plasma technology applications in selected Canadian industrial sectors and processes were carried out in this study. Also, the Canadian company which has the potential capability of manufacturing or supplying plasma generating systems has been identified in accordance with the objectives of the study.

On the basis of the review and the assessment, the following conclusions and recommendations may be drawn:

- Plasma processing of materials is a growing field which encompasses a broad range of applications including direct smelting of mineral (metal) ores; conversion of hydrocarbons to chemicals and synthetic fuels; melting-refining of super-alloys and refractory metals; and synthesis of extra-pure, uniformly sized powders for production of advanced ceramics and other high technology materials.

- At present, a number of pilot-plants and commercial-scale plasma installations are already in operation in several countries, although none in Canada yet. Also, a number of plasma-generating systems or plasma reactors (furnaces) are currently available commercially in the U.S.A., Sweden, Japan, G.D.R., Austria, F.R.G., France, U.K., U.S.S.R., and other countries. In Canada, the Québec based manufacturing company, Volcano Inc., has a potential capability for supplying plasma-generating systems. Currently, Volcano Inc., is negotiating licencing from Aerospatiale, France, for plasma generators of power input up to 5 MW.

- In Canada, conditions are favourable for plasma technology applications because of the availability and relatively low cost of electricity (at present in Québec and Ontario, even a surplus of electricity exists).

- Canada possesses natural resources such as mineral ores (including those containing refractory metals), natural gas and coal, plasma processing of which might be advantageous.

- Research on plasma fundamentals and applications has been carried out in Canada since the 1960s. Today, several Canadian Universities, Industrial and Governmental Centres are involved in plasma research. The collective results of the Canadian research and development in plasma are fully comparable in quality and degree of knowledge to those of the rest of the industrial world.

- Canadian research and development efforts have already resulted in some steps towards commercialization of plasma technology:

  - The transferred-arc direct current (DC) plasma reactor (later given the trade name PLASMACAN) was developed at Noranda Research Centre, Quebec. The reactor patents were assigned to IREQ (Institut de Recherche d'Hydro-Québec) which in turn gave the worldwide licence (except Canada) to Davy McKee, U.K. A 1-MW nominal capacity plasma reactor based on the Noranda configuration has been designed, built and tested at power input up to 250 kW for iron ore and ferromanganese ore smelting by Davy McKee Research and Development in Stockton-on-Tees, England. Another 250-kW PLASMACAN reactor was designed and installed at the University of Sherbrooke for testing on various industrial application. The reactor is presently undergoing trial operations.
  - The University of Toronto extended-arc alternating current (AC) plasma reactor is another Canadian development towards commercialization: a 1-MW plasma demonstration facility based on the University of Toronto reactor design has been built and is undergoing preliminary trials at the Ontario Research Foundation.
  - Also, INCO and ASEA are collaborating on a project to investigate the possibility of producing nickel using plasma technology: a pilot-plant including a 900-kW plasma furnace with single graphite electrode has been built by INCO. An experimental program is planned to start at the end of 1986. The work is supported by the National Research Council of Canada.

- In iron-ore reduction, both plasma-upgrading of conventional blast furnaces and new direct plasma iron-ore smelting processes have been developed. A concept of plasma-upgrading of blast furnaces using plasma injection of reducing overheated gas, the so-called PIROGAS process, has been developed and demonstrated by Centre de Recherche Métallurgique, Belgium. The Steel Company of Canada (STELCO) has been participating in this development. Aerospatiale, jointly with Jeumont-Schneider and Electricité de France have tested plasma heating of blast-air using a 2.1-MW mobile plasma unit developed by these companies. New direct plasma iron-ore smelting processes have been demonstrated on a pilot-plant level by Bethlehem Steel, U.S.A.; SKF Engineering, Sweden; and Davy McKee, U.K.

- The PIROGAS process demonstrated in an experimental blast furnace has shown the possibility of reducing coke consumption by 385 kg/t of hot metal produced (from 470 kg/t down to 85 kg/t). Preliminary tests have shown that about 66.3 m^3 of natural gas and 137.2 kWh of electricity can replace 100 kg of coke using the PIROGAS process. Although no drastic reduction of production cost would be anticipated at current prices of electricity, natural gas and coke in Ontario, plasma upgrading of existing blast furnaces may be quite attractive due to obsolescence of some of the coke ovens in integrated steel plants located in Ontario coupled with increasingly stringent environmental protection requirements. (Data on plasma blast-air heating in France are not available yet.)

- Bethlehem Steel has shown that using the falling-film DC plasma reactor, one-step direct plasma iron-ore smelting could result in production of "semi-steel" with low carbon and sulphur contents, practically eliminating coke requirements. Nevertheless, the electricity consumption was too high for economic steelmaking (about 3000 kWh/t of hot metal produced). Pre-reduction of iron ore using process off-gases has been suggested by both SKF Steel Engineering for their direct plasma iron-ore smelting process PLASMASMELT and by Davy McKee, U.K. - IREQ (Hydro-Québec), Canada for their integrated PLASMACAN-FIOR process, to reduce electricity consumption to more acceptable levels.

- Test results of SKF PLASMASMELT process based on use of a coke-filled, refractory-lined shaft with DC plasma generators attached to the tuyeres, predicted coke consumption of about 50 kg/t of hot metal produced at an electricity consumption of 1150 to 1200 kWh/t of hot metal (assuming 50% pre-reduction of iron ore with process off-gases).

- Preliminary cost comparisons of conventional steelmaking processes based on coke oven - blast furnace - basic oxygen process (BOP) technologies with direct plasma iron-ore smelting using PLASMASMELT-BOP, and INRED-BOP, ELRED-BOP technologies (i.e., two other direct iron-ore smelting processes competing with PLASMASMELT) have shown that both the lowest investment per metric ton of liquid steel produced annually and production cost may be expected using PLASMASMELT-BOP processes in Canada. Thus, application of direct plasma iron-ore smelting processes which allow efficient reduction of finely divided particles of pre-reduced iron-ore (i.e., without pelletizing or sintering required for conventional or plasma upgraded blast furnaces) is the most promising way to reduce investment and product cost for iron-ore smelting. It is difficult to anticipate, however, that under present economic conditions, the Canadian integrated steel producers will undertake such a major technological change in iron-ore smelting. This is mostly due to the huge capital which is tied up in existing blast furnace facilities. Direct plasma iron-ore smelting should be considered for new Canadian iron-ore smelting plants.

- Application of plasma technology may be advantageous for production of refractory metals and their ferro-alloys (particularly because the high temperatures required for melting of these materials are easily achievable in thermal plasma systems).

- Plasma ferrovanadium production has been demonstrated. Bethlehem Steel, U.S.A., has tested production of ferrovanadium from vanadium pentoxide using 100-kW and 500-kW falling-film DC plasma reactors. The best results achieved in 100 kW reactor were: vanadium recovery as metallics

90%, energy consumption 5510 kWh/t (2.5 kWh/lb) of vanadium (8595 kWh/t with post heating). The ferrovanadium produced in 500 kW plasma reactor contained 42.9 to 55.2% vanadium, 53.0 to 36.1% iron, 2.9 to 6.8% carbon, at energy consumption 7714 kWh/t to 5951 kWh/t. The tests carried out in a smaller scale Noranda configuration plasma reactor resulted in ferrovanadium containing 79.4% vanadium, 18% iron and 0.6% carbon.

- Production of ferrovanadium and ferronickel from oil-fired boiler fly ash was investigated at the University of Toronto using AC extended-arc flash plasma reactors with hollow graphite electrodes, at power inputs of 15-70 kW. In the 70-kW plasma reactor with anthracite used as a reductant, 90.3 to 95.8 wt% metal recovery (43.2 to 62.5 wt% vanadium) has been achieved in the tests on one-step ferro-nickel-vanadium production. The average energy consumption was equivalent to about 16 500 kWh/t of ferro-nickel-vanadium.

- Fly ash derived from Alberta's oil-sands plants contains substantial amounts of vanadium pentoxide. The vanadium associated with the annual production of Suncor and Syncrude plants which are in operation today amounts to about 2000 tonnes. This amount could cover not only Canadian market needs in vanadium (about 300 t/y) but also make a substantial impact on the world vanadium market. Plasma production of ferrovanadium from this fly ash has potential and may be one of the challenging opportunities for plasma technology applications in Canada.

- Plasma ferrochromium production has been demonstrated in pilot plants and commercially. Extensive plasma technology development towards commercial production of ferrochromium has been carried out in South Africa by the Council of Mineral Technology (MINTEK) in conjunction with Middelburg Steel and Alloys. Successful tests have been carried out at Tetronics, U.K., in a 1.4-MVA plasma furnace; and at MINTEK, in a 100-kVA experimental plasma furnace with a hollow graphite electrode, as well as a 3.2-MVA pilot-plant plasma facility. A 20-MVA plasma furnace with a centrally located hollow graphite electrode has been in operation

at the Krugersdorp Division of Middelburg Steel and Alloys since the end of 1983. Production of several thousand tonnes of ferrochromium has been reported. The furnace was developed and supplied by ASEA, Sweden.

- The PLASMACHROME process was developed and demonstrated on a pilot-plant level by SKF Steel Engineering, Sweden. The first commercial PLASMACHROME plant is being built by SKF in Malmo, Sweden. The plant is designed for production of 78 000 t/yr of ferrochrome. The energy consumption during the pilot-plant tests was in the range 5300 to 5800 kWh/t of ferrochrome produced.

- Plasma production of ferrochromium may have a potential for application in Canada based either on Canadian resources of chromite or chromite imported from abroad, using relatively low-cost Canadian electricity.

- Plasma production of ferromolybdenum from molybdenite concentrate has been investigated using the Noranda configuration plasma reactor. The best results achieved were 99.96% decomposition efficiency (0.03% sulphur) at an energy consumption of 12 MWh/t of molybdenum in the feed. Nitrogen was used as a plasmagen gas.

- A conceptual plant design for plasma production of 2268 t/yr (5 million lb/yr) of molybdenum contained in the product (50% Mo in FeMo, 0.15% S) was carried out by the Noranda Research Centre in collaboration with an independent engineering company based on results obtained using the Noranda configuration experimental reactor. The preliminary cost estimate in March 1985 Canadian dollars predicted the total plant investment of about Can.$ 15 million. The estimated product cost is Can.$ 14.88/kg Mo in FeMo. The estimated cost of the plasma reactors (including feeding, tapping, power supply and gas supply systems) comprises only 15% of the total plant investment, the cost of electricity comprises between 15% and 18% of the direct operating cost of the plant (at electricity cost of $0.024/kWh and $0.03/kWh respectively).

- Plasma production of niobium and tantalum or their alloys is still at the laboratory stage of research. Investigation of zirconium and titanium metal plasma production has shown the technical feasibility to produce dense metal from the metal tetrachloride using a three-step plasma process instead of the multi-stage Kroll process commercially used for production of zirconium and titanium sponge. If zirconium containing naturally occurring hafnium (i.e., without removal of hafnium) is acceptable, the cost of the metal produced using plasma technology would be as low as $4-5/kg according to McGill University Plasma Group estimates. The price of zirconium sponge produced via the commercial Kroll process is about $16/kg.

- Titanium dioxide pigment production is of great importance for Canada because of abundant resources of ilmenite ore which is the feedstock (after upgrading) for titanium dioxide. A commercial plasma oxidation of $TiCl_4$ has been developed by the Tioxide Group in the U.K. and the process is used in the Greatham plant in England. At the Tioxide Canada plant, however, another technological process is used for which $TiCl_4$ oxidation is not applicable.

- Plasma melting/remelting furnaces are operating in several countries at both pilot-plant and demonstration/commercial-scale levels. A comparison of the performances of conventionally used electric-arc furnaces and the 10-tonne plasma furnace at Freital, G.D.R. confirmed the substantial advantages of plasma furnaces. In particular, up to 30% lower capital investment compared to a modern Ultra High Power (UHP) electric-arc furnace, elimination of shock loading of the electric power supply, higher melting efficiency and superior recovery of the alloy metals, lower level of noise and other advantages were shown.

- Several plasma melting/remelting DC plasma furnaces with torches (cathodes) installed in the sidewalls and a single anode in the bottom are in operation at Freital, G.D.R., for a number of years now, ranging in capacity from 5 tonnes to 30/40 tonnes. A 45/60-tonne plasma furnace of this type is in operation at Voest Alpine, Linz, Austria. The estimated melting-down energy for 50- to 100-tonne plasma furnaces (input power 25 to 40 MW) is below 400 kWh/t.

- Daido Steel, Japan has developed and is using plasma-induction furnaces (PIF) commercially. According to Daido Steel information, the PIF melted material can be considered equivalent to that produced in the industrial-size vacuum induction melting furnaces and is superior to that produced in electric-arc furnaces and, subsequently, vacuum degassed. The reported alloy recovery in the melted material is higher than 95%.

- Krupp Research Institute (Krupp Forschungsinstitut) in Essen, F.R.G., has been developing AC three-phase plasma furnaces for melting/remelting operations, as well as for ladle heating. A 3-tonne pilot furnace with Krupp's AC transferred-arc plasma generators (torches) mounted on the roof of the furnace (current up to 4000 A) was tested for scrap melting. Positive results have been achieved with little lining wear, low noise and flicker levels. A 10-tonne, three-phase AC plasma furnace is under construction at Krupp Steel Works in Siegen to be tested with Krupp's 6 kA and 12 kA AC plasma generators/torches which are under development.

- Tetronics Research and Development Ltd., U.K., has tested the melting/remelting of ferromanganese fines using their 3-MVA DC plasma furnace with precessing plasma generator (torch). The power input was up to 696 kW. It was confirmed experimentally that metallic ferro-alloy fines can be directly recycled to the plasma furnace for remelting and production of ferro-alloy free from slag and suitable for use in the

steel industry. The melting energy approached the predicted value of 410 kWh/t of fines. On average 19% of the manganese in the raw materials reported to the slag and 3% to the exhaust gas and baghouse filter.

- MINTEK, South Africa has tested successfully the melting of ferromanganese particles (smaller than 6 mm) using a 1400-kVA Tetronics plasma furnace and a 100-kVA MINTEK plasma furnace with graphite electrode (cathode). Also, the possibility of high-carbon ferromanganese and silicon fines co-melting to produce silicon-manganese alloys from off-grade metal fines has been investigated and confirmed.

- There is a potential for plasma furnace application in Canadian industries for melting/remelting and other operations instead of conventional electric-arc furnaces, due to the technical and investment advantages of plasma furnaces. This is particularly true for new installations when lower investment requirements could be fully realised.

- Plasma treatment for recovery of high-value alloying elements from aerospace, gas turbine, high-resistance bearing, high-temperature compressors and other scraps and production rejects may be a potentially very lucrative industry in Canada. This plasma treatment is basically a melting operation. Some refining can be effected, if needed, by addition of suitable fluxes. The value of these recovered alloys ranges from US $20/kg to US $40/kg, as reported by United Technologies, U.S.A. The plasma processing in this case would have the additional advantage of eliminating the remaining traces of undesirable volatile impurities such as antimony, arsenic, bismuth, sodium, potassium, and magnesium. Because of high vapour pressure, these impurities would be vented off with the effluent plasmagen gas, as demonstrated by the Noranda Research Centre.

- Plasma melting in application to cupolas is under development in the U.S.A. The experimental program to demonstrate the advantages of the plasma-fired cupolas in relation to large foundries associated with the automobile industry was initiated in October 1983, jointly sponsored by Westinghouse, Electric Power Research Institute, Modern Equipment Company and General Motors. Plasma firing of cupolas would substantially reduce the coke consumption, as well as air pollution. Also, operating cost could be reduced by about 30%, according to preliminary cost estimates made by the process developers. In Canada, however, the potential for such a plasma application appears to be quite limited since the cupolas are numerous but small (on average, about 10 t/h of molten iron capacity, the largest about 45 t/h) and it is difficult to justify the investment required for converting these small cupolas to plasma firing.

- Plasma heating in ladles may be another potential plasma application in Canada related to melting/remelting/refining. The ASEA, Sweden, DC plasma furnace with a central graphite electrode and a hearth connection (anode) has been adapted specifically to ladle heating. Plasma Energy Corporation, U.S.A., has demonstrated plasma ladle heating using their plasma generators (torches). SINTEF, Norway has developed an immersed plasma torch for ladle heating. A 1-MW SINTEF plasma-arc heater has been installed at Hella Sweteverk, Norway in an 8-tonne ladle.

- Plasma conversion of hydrocarbons has been the first and earliest commercial plasma application. The Huels Chemical Company (Chemische Werke Hüls), F.R.G., has been producing acetylene from hydrocarbon gases in DC arc plasma reactors since 1939. The present Huels production is estimated at 120 000 t/yr of acetylene, 50 000 t/yr ethylene and 500 million m^3/yr hydrogen as by-product using continuously 19 arc-plasma reactors, 8.5 to 10 MW each. E.I. Dupont de Nemours and Co., operated a "rotating electric-arc process" at Montagne, Michigan, U.S.A., to produce 22 686 t/yr (50 million lb/yr) of acetylene from natural gas. The Dupont facility was closed down in 1973 because of poor economics

and operating problems. AVCO, U.S.A., has developed an electric-arc plasma reactor for conversion of coal to acetylene and demonstrated the process in 200-kW and 1-MW plasma reactors. Later, a similar development was initiated by the Huels Chemical Company, jointly with Bergbau Forschung, F.R.G. Tests have been carried out in 80-kW and 500-kW DC arc-plasma reactors.

- A commercial installation for plasma conversion of hydrocarbon gases to reducing gas for direct iron-ore reduction plant of USCO Corporation, South Africa is under construction. The installation is based on five 8.5-MW Huels arc-plasma reactors designed for steam reforming of hydrocarbon gases. One of these plasma reactors is currently at a start-up operation.

- Conversion of coal to synthesis gas has been reported by Plasma Energy Corporation, U.S.A., using their plasma reactor.

- In Canada, plasma conversion of natural gas to gasoline has been investigated by SNC Inc., in a cost-shared study sponsored by CANMET, Energy, Mines and Resources Canada. Plasma gasification of coal, heavy oil, peat and wood have been under investigation at McGill University, University of Sherbrooke and PAPRICAN. An experimental program on conversion of Canadian coke to acetylene in a hydrogen plasma reactor was also sponsored by CANMET.

- Preliminary assessment of gasoline production from natural gas via conversion of the natural gas to acetylene, using three alternative reactors (Huels reactor with the natural gas as a plasmagen, Westinghouse plasma reactor with hydrogen as a plasmagen and the resistance-heater reactor) has shown that for a plant location in Québec and a plant capacity of 12 500 bbl/d of gasoline, the estimated product cost of gasoline ranges from 43 to 50 ¢/L which is certainly higher than the existing cost of gasoline (30 to 35 ¢/L) from crude oil via conventional technology. (The product cost and plant investment depend

only marginally on the type of reactor used.) The plasma route of gasoline production from natural gas would result in substitution of about 18 000 bbl/d of crude oil equivalent or about 6.0 million bbl/yr of crude oil, for a 12 500-bbl/d-of-gasoline plant.

- Preliminary assessment was also carried out for production of acetylene as an intermediate product from natural gas via Huels plasma reactor and from coal via AVCO plasma reactor. In both cases plant capacities of 22 686 t/yr (50 million lb/year) and 13 611.6 t/yr (300 million lb/year) were considered. Plant locations in Quebec and Alberta were assumed using natural gas as a feedstock and only Alberta was considered using coal as a feedstock (because of the absence of coal resources in Québec). Acetylene can be converted to a variety of chemicals. The choice of end-product for Canada would be dictated by market requirements and such an analysis is beyond the scope of the present study. Therefore, in this study the assessment was done for two selected cases only: production of Reppe-type chemicals such as butyndinol, butanediol, tetrahydrofuran, polyvinyl, pyrolidone, etc., based on 50 million lb/yr acetylene plant; and production of commodity (i.e., large-volume) chemicals based on 300 million lb/yr acetylene plant.

- The estimated product cost of acetylene (in March 1985 Canadian dollars) from 50 million lb/yr plant is 53.1 ¢/lb in Quebec and 54.7 ¢/lb in Alberta using natural gas as a feedstock. These costs are much lower compared to 70 to 80 ¢/lb of acetylene from other technological routes, e.g., calcium carbide or partial oxidation routes for acetylene. Such cost differentials make plasma acetylene production in Canada from natural gas quite attractive as a feedstock for low-volume specialty Reppe-type chemicals. (The estimated product cost of plasma acetylene from coal at 50 million lb/yr plant is 67 ¢/lb. That is due to additional processing steps required as compared to plasma acetylene production from natural gas. Therefore, coal conversion to acetylene using plasma is less attractive for Canadian conditions.) It should be

noted that acetylene cannot be transported over long distances (except in special cylinders) and, therefore, the acetylene plant would have to be located adjacent or in close proximity to a chemical plant using acetylene as a feedstock.

- The estimated cost of acetylene (in March 1985 Canadian dollars) from 300-million-lb/yr plant is approximately the same for plants using natural gas or coal as feedstocks and located in either Québec or Alberta. The estimated product cost ranges between 37.6 ¢/lb and 39.0 ¢/lb. Taking into account that for commodity chemicals the acetylene as a feedstock must compete with ethylene which is available today at a price of 19 to 20 ¢/lb, the plasma acetylene route as a feedstock for production of commodity chemicals does not appear to be attractive.

- A new area has been opened in the development and application of advanced (engineering) ceramics due to their superior properties and, therefore, potential possibility to replace traditional engineering materials such as metals, particularly in heat engines, gas turbines, diesel and gasoline engines, etc. The estimated sales of advanced ceramic materials worldwide by 1995 is above 10 to 12 billion dollars.

- Up to 70-80% of the total manufacturing cost of an engineering ceramic part is due to finishing operations (e.g., in the case of ceramic turbocharger rotor). The single largest factor contributing to high cost of finishing operations is impure, agglomerated starting powders from which advanced ceramic materials are formed, and wide particle distribution. Application of plasma synthesis may be one of the most appropriate ways to produce pure, non-agglomerated, fine (dia = 0.1 to 1.0 micron) particles with narrow size distribution and equiaxed in shape, as shown in a number of experimental investigations worldwide. Plasma spheroidization of coarser non-spherical particles from high-melting temperature materials is another approach to produce fine, equiaxed particles. The experimental investigations, however, on which

technical data are available, were carried out until now on a laboratory scale and many problems have to be solved before commercial application of plasma technology in production of advanced (engineering) ceramic materials can be considered. This plasma application should be considered in Canada as a long-term research, development and demonstration strategy.

RECOMMENDATIONS

- Development towards commercialization of ferro-alloys plasma production (including research support needed) is recommended as an area which could offer, probably in the relatively short term, a promising possibility for plasma technology applications in Canada and the setting up of new indigenous Canadian industries based on this technology.

- Ferrovanadium plasma production (and R&D to support this development), as the first candidate ferro-alloy is recommended based on vanadium recovery from fly ash obtained from Alberta's oil-sands plants in operation today. A techno-economic assessment of ferrovanadium plasma production from Alberta oil-sands plants fly ash versus other known processes (supported by preliminary tests on plasma vanadium recovery from this fly ash) is recommended before embarking on a commercialization program in order to define the economic potential and benefits in Canada for this plasma application.

- Plasma treatment for recovery of high-value alloy scraps is recommended as another relatively short term development in industrial plasma technology application in Canada for a potentially very lucrative industry.

- Plasma conversion of natural gas to acetylene as an intermediate product for low-volume specialty chemicals has a potential for industrial applications in Canada and is recommended for locations where corresponding end-use of the acetylene produced is in close proximity to the acetylene plant and is supported by infrastructure and market.

- Plasma application for production of advanced ceramics may have a great potential in Canada. Many problems, however, have to be solved before commercial application based on today's laboratory experimental results. An extensive RDD (Research, Development and Demonstration)

program is recommended in this area, targeted toward commercial applications around 1990-1995 when tremendous market opportunities in advanced ceramic materials are expected.

- Replacement of conventional electric-arc furnaces by plasma furnaces should be supported, particularly for new installations, where up to 30% capital investment saving may be realized.

- Direct plasma ore smelting in Canada should be considered mostly for a new iron-ore reduction facilities. Plasma upgrading of existing iron-ore blast furnaces in Canada is recommended as a temporary approach to reduce coke consumption.

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CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

This survey of the potential of plasma technology applications in Canada was carried out by the Technical Development Department, SNC Inc., for the Canada Centre of Mineral and Energy Technology, CANMET, Energy Mines and Resources, Canada.

Thermal plasma processing of materials involves a gas in the plasma state characterized by a higher energy content than that of solids, liquids and ordinary gases. Application of plasma technology has, therefore, a unique advantage when processing materials at high temperatures is required, in particular at temperatures above those obtainable with chemical flames or resistance heater systems, in either inert or reactive environments. Some other potential advantages of thermal plasma applications for processing of materials are:

- Partial or complete substitution of fossil fuels (e.g. metallurgical coal, coke, oil) by electricity and reduction of imported fuels;
- high electrical efficiency;
- ability to process finely divided materials;
- possibility to achieve environmentally acceptable conditions by using closed plasma reactor systems;
- reduced capital intensity due to direct heat transfer at plasma temperatures;
- high reaction rates and shorter residence time, and others.

Owing to the substantial consumption of electricity per unit of product required, however, the availability and cost of electricity is an important (sometimes critical) factor from a standpoint of technical and economical feasibility of plasma technology industrial applications. In Canada, the situation

is quite favourable in this respect due to availability and relatively low-cost of electricity. (See Figure 1-1.) At present, in Québec and Ontario even a surplus of electricity exists.

Canada also possesses natural resources such as iron ore, ores containing strategic or refractory metals, natural gas and coal, plasma processing of which might be potentially applicable and advantageous.

At present, several commercial-scale plasma processes are in operation or being installed in a number of countries such as Japan, Sweden, U.K., U.S.S.R., G.D.R., Austria, South Africa and others, although none in Canada, despite availability and relatively low electricity cost, extensive plasma research and natural resources.

The main objectives of this study, therefore, are:

- to determine the techno-economic constraints for commercialization of plasma technology in Canadian industrial sectors;
- to identify the Canadian industrial sectors and processes for which application of currently available plasma technology has realistic potential technical and economic benefits;
- to assess the capabilities of Canadian manufacturers and/or suppliers to provide plasma generating systems or system components; and
- to recommend research and development strategy for implementation of plasma technology in the Canadian industrial sectors or processes identified above.

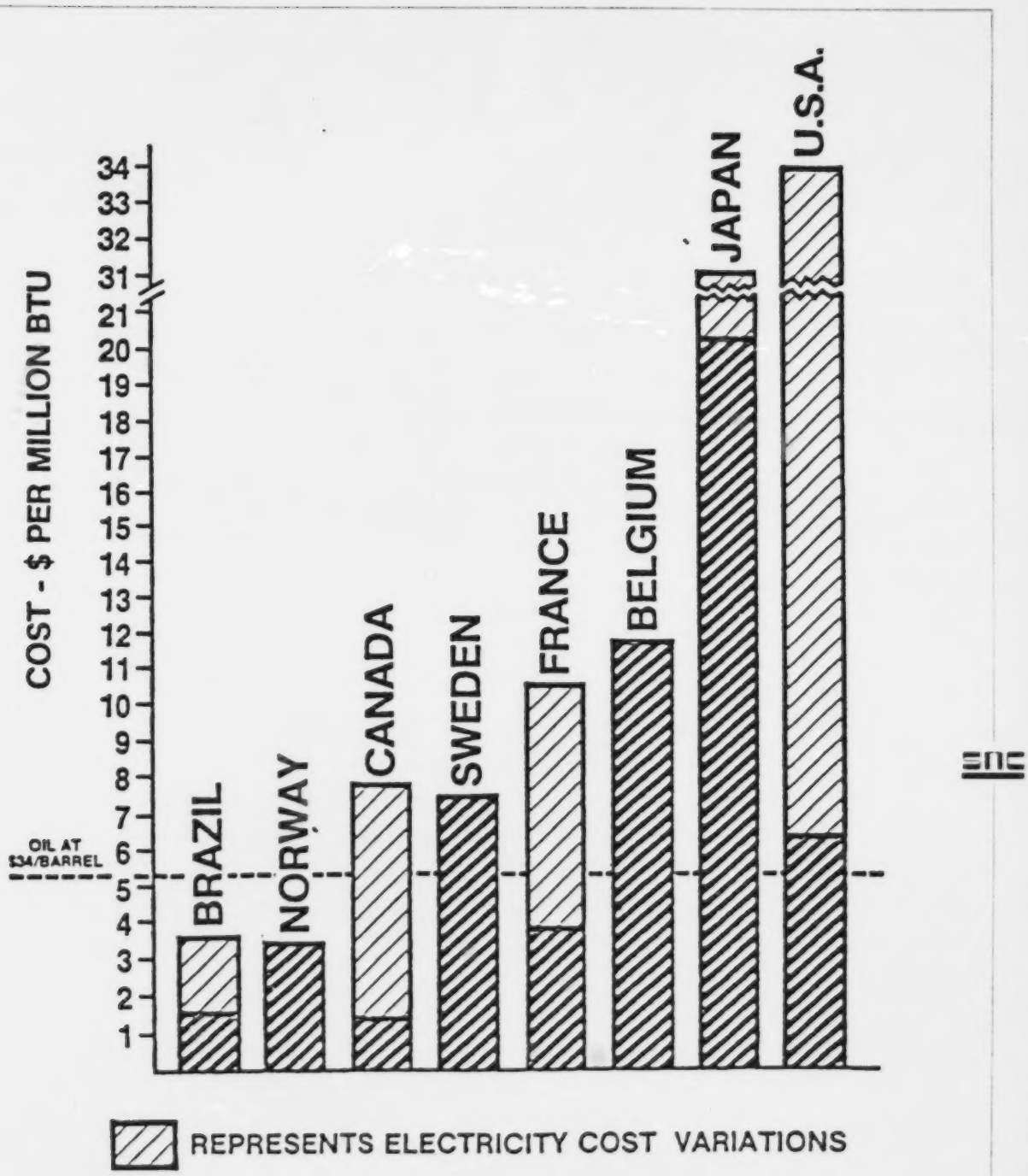


Figure 1-1 Electricity Cost for Various Countries

Source: S.L. Thunberg, W.H. Reed, W.J. Melilli, T.N. Meyer, and M.G. Fey, "The Potential Contribution of Plasma in Decreasing Coke Rate in Blast Furnace", Westinghouse Applied Plasma System, COBRAPI Seminar, April 25-26, 1984.

Thermal arc-plasma systems and processes are considered mostly in this report. These are, in general, the high electricity-consuming devices, application of which may contribute to further efficient use of Canadian extended electrical power systems.

Plasma processing in extractive metallurgy (including plasma upgrading of existing technologies and new plasma processes in production of iron, ferroalloys and refractory metals, etc.), melting/remelting operations and hydrocarbon processing are included in the scope of this report. Also, the potential of plasma application for production of advanced ceramic powders (which has a rapidly growing worldwide market) is briefly discussed in the report. Plasma treatment of wastes, including metal dusts, is beyond the scope of this study.

Thermal plasma processing in arc welding, cutting and plasma spraying are well-established commercially and therefore, not considered.

The scope of this study is limited to plasma processes which have been demonstrated either commercially, or on a pilot-plant scale, or have been investigated extensively in the laboratory. Brief descriptions of these currently available plasma processes or plasma generators/reactors are given to an extent which enable comparison of the plasma technologies with corresponding conventional technologies. New plasma developments (including those under research in Canada) are beyond the scope of this study.

1.1 PLASMA RESEARCH IN CANADA

Research on plasma fundamentals and plasma applications has been carried out in Canada since the 1960s, when Dr. W.H. Gauvin initiated the programme in this field at McGill University in Montréal, and then organized a plasma group at the Noranda Research Centre in Pointe-Claire, Québec. The first Ph.D. student in this field graduated from McGill University in 1962.

At present, the plasma research and development is being carried out at several Canadian universities and industrial research centres.

The major plasma centres (groups) in Canada are listed below:

Universities Plasma Centres

McGill University
University of Sherbrooke
University of Toronto
École Polytechnique (Montréal)
Queen's University
McMaster University
University of Québec (Chicoutimi)
Royal Military College of Canada (Kingston, Ontario)

Industrial/Government Plasma Centres

Extractive Metallurgy Laboratory, CANMET
The Research Institute of Hydro-Québec (IREQ)
Ontario-Hydro Research
Industrial Materials Research Institute (IMRI)

The Hydro-Québec and Ontario-Hydro plasma centres are set up to carry out joint plasma development projects with interested Canadian industries.

Both centres are equipped with laboratory plasma systems (Noranda-IREQ DC plasma furnaces at IREQ, and 80-kW Acurex segmented DC torch at Ontario Hydro's plasma laboratory). Both centres will also have 150-250 kW DC plasma torch systems supplied by the Plasma Energy Corporation [1].

In recognition of Canadian achievements in the field, Canada was selected as the host for the 6th International Symposium on Plasma Chemistry, ISPC-6, 1983 held at Sherbrooke and McGill Universities where especially intensive thermal plasma programmes are being carried out.

At the next major world event on plasma science and technology, the 7th International Symposium on Plasma Chemistry, ISPC-7, July 1985 held in Eindhoven, The Netherlands, over 15 presentations were made by representatives of Canadian universities, government and industry.

In addition to substantial results obtained on plasma fundamentals, diagnostics and laboratory evaluation of various plasma applications, Canadian research and development efforts have resulted in some steps towards commercialization of plasma technology.

The transferred-arc DC plasma reactor developed at Noranda Research Centre and patented by Gauvin W.H. and G.R. Kubanek [2] was selected by Davy McKee, U.K. and IREQ for scale-up and further commercialization. The reactor patents were assigned to IREQ which in turn gave the worldwide licence (except Canada) to Davy McKee, U.K. Subsequently, a 1-MW nominal capacity plasma furnace was designed and built by Davy McKee Research and Development, U.K.

This furnace was tested on production of ferro-alloys and direct iron-ore smelting at power input up to 250 MW (see details in Chapters 2 and 3).

Another 250-kW plasma furnace of Noranda configuration, under the trade name PLASMACAN was designed and built by the University of Sherbrooke to be used in their plasma testing facility on various industrial applications [3]. A 1-MW plasma demonstration facility based on the PLASMACAN furnace to be installed at IREQ is under negotiation. The first project proposed for testing at this plasma facility is an integrated iron-ore pre-reduction based on Davy McKee's FIOR (Fluidized-Bed Iron-Ore Reduction) system and direct iron-ore smelting using PLASMACAN [4,5].

Another Canadian development is an extended-arc AC plasma reactor with hollow graphite electrodes, developed at the University of Toronto (Alcock, McLean et al.) [6]. The reactor was tested at relatively low power levels (up to 100 kW) for smelting and refining of ferro-alloys, recovery of metals from steel-mill baghouse dust, etc., (see details in Chapter 2 and 4). Based on the University of Toronto design, a 1-MW plasma demonstration facility is undergoing trials. The facility is installed at the Ontario Research Foundation, Toronto and will be operated by a consortium formed by industrial companies [7]. The 900-kW plasma furnace with hollow graphite electrode supplied by ASEA Sweden is installed at the INCO, Canada pilot-plant. The furnace will be tested on direct plasma reduction of nickel oxide and other applications of nickel production [134]. The work is supported by the National Research Council of Canada.

In the course of the current study, assistance was obtained through direct contacts and collaboration established with plasma centres and groups in Canada. The collective results of the Canadian research and development efforts are fully comparable in quality and degree of knowledge with those of the rest of the industrial world; and will definitely contribute to the implementation of plasma technology potential in Canada, in particular in those Canadian industries identified and discussed in this study.

1.2 STRUCTURE OF THE REPORT

This report comprises seven chapters.

Chapter 1 - Introduction (including an outline of plasma R & D in Canada), as well as objectives and scope of the study.

Chapter 2 - Overview of currently available plasma technology systems (including introduction to plasma fundamentals).

Chapter 3 - Plasma applications in iron and steel production.

Chapter 4 - Plasma applications in production of refractory metals and ferro-alloys

Chapter 5 - Plasma applications in melting/remelting operations

Chapter 6 - Plasma processing of hydrocarbons

Chapter 7 - Potential for plasma applications in production of advanced ceramic materials.

CHAPTER 2

PLASMA AND CURRENTLY AVAILABLE

PLASMA TECHNOLOGY SYSTEMS

CHAPTER 2

PLASMA AND CURRENTLY AVAILABLE

PLASMA TECHNOLOGY SYSTEMS

2.0 PLASMA AND CURRENTLY AVAILABLE PLASMA TECHNOLOGY SYSTEMS

2.1 PLASMA

Plasma is an ionized gas containing electrons, positive and negative charges, and neutral species. Although there are free electric charges in a plasma, negative and positive charges compensate each other. Basically, a plasma is electrically neutral, a property known as "quasi-neutrality". In contrast to an ordinary gas, which is normally non-conductive, the free electric charges in the plasma state of the gas give rise to high electrical conductivities that may even surpass those of metals. The plasma state is frequently referred to as the fourth state of matter, since more than 99 per cent of the universe known to man is in the plasma state [8].

Generally, plasmas may be subdivided into two types: "hot" or "equilibrium" plasma which is characterized by an approximate equality of heavy particle temperatures (T_h) and electron temperatures (T_e); and "cold" or "non-equilibrium" plasma which is characterized by high electron temperatures and rather low "sensible" temperatures of the heavy particles ($T_e \gg T_h$).

It should be noted, that in the case of hot or so-called thermal plasmas, the thermodynamic state of the gas approaches local thermodynamic equilibrium (LTE). LTE is characterized not only by the temperature equality of electrons and heavy particles ($T_e = T_h$), which is the kinetic equilibrium, but also by the chemical equilibrium; i.e., particle concentrations in a LTE plasma are only a function of the temperature.

Typical examples of the thermal plasmas are those produced in high-intensity arcs or in radio frequency (RF) high pressure (above 0.1 MPa) discharges. Thermal plasma temperatures are quite high, up to 15 000 K and even higher. Therefore, thermal plasma application is particularly advantageous where materials

processing at high temperature is required, in either inert or reactive environments (melting/remelting of high melting-point materials, spraying, synthesis of inorganic materials for advanced ceramic powders, etc.,).

Cold or non-equilibrium plasmas are those produced in various types of glow discharges, low pressure RF discharges, and corona discharges. Non-equilibrium plasma temperatures are between ambient and a few hundred degrees Kelvin (K).

The approximate range of electron temperatures and electron densities of natural and man-made plasmas are presented in Figure 2-1. The electron temperatures are given in units of electronvolts (1 eV corresponds to an electron temperature of approximately 7740 K).

As a general criterion for the existence of hot (thermal) or cold (non-equilibrium) plasma, the ratio of electrical field strength to pressure (E/P) or electrical field strength to particles number density (E/N) may be used [8,9]. This criterion reflects the energy exchange process between electrons and heavy particles in a plasma. High electric fields tend to increase the excess energy of the electron gas, therefore thermal plasmas are characterized by small values of E/P or E/N. For cold plasmas, values of these parameters are higher, usually by several orders of magnitude. Figure 2-2 shows the separation of electron and heavy particle temperatures in an electric arc as a function of pressure.

As mentioned earlier (see Chapter 1), the technological applications of thermal plasmas produced in currently available high intensity electric-arc plasma generators and systems are considered mostly in this study.

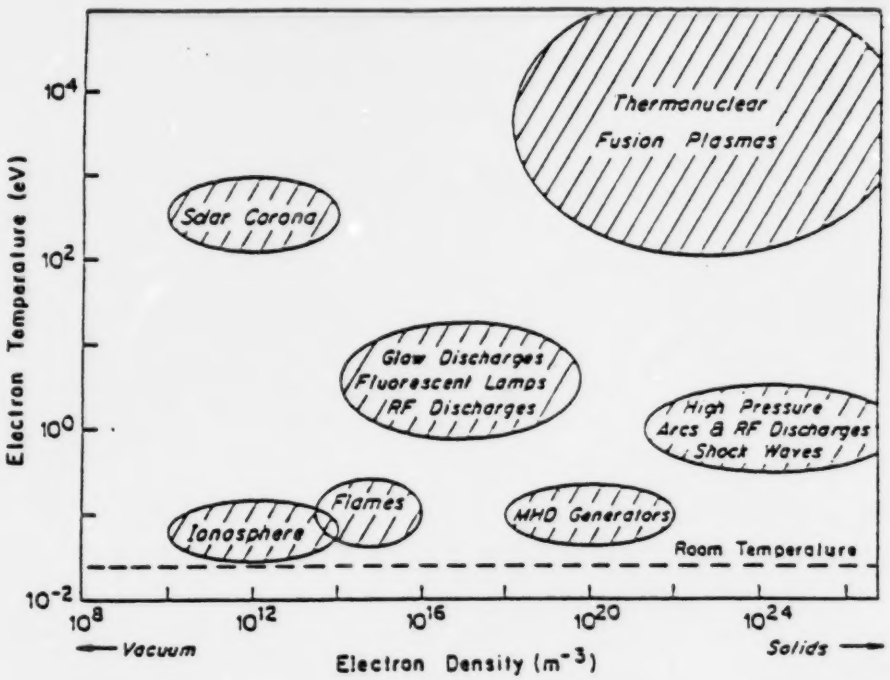


Figure 2-1 Classification of Plasmas

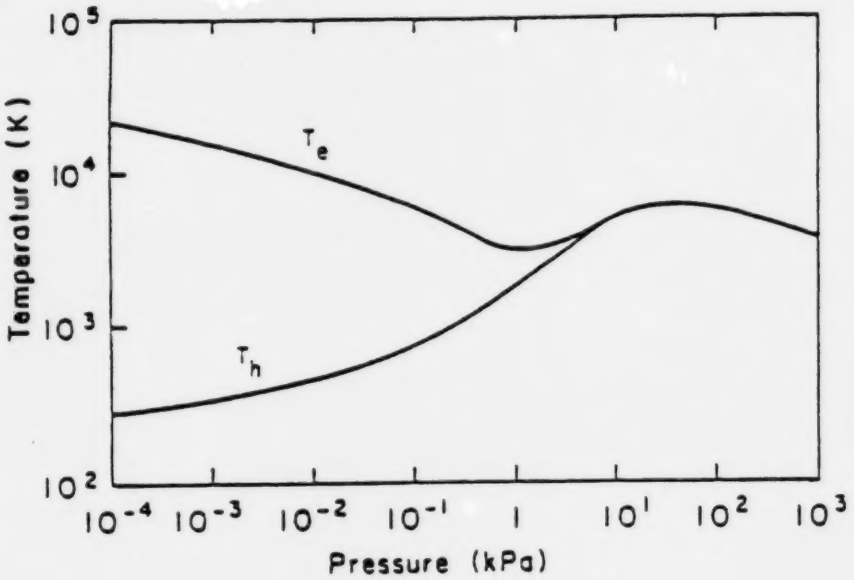


Figure 2-2 Behavior of Electron Temperature (T_e) and Heavy Particle Temperature (T_h) in a Plasma Arc

Principles and brief descriptions of some of these plasma generators and reactors (furnaces) are presented below.

2.2 PLASMA GENERATORS

A plasma-arc generator is a device for converting electrical energy into the thermal energy of a gas passing through an electric arc generated between two electrodes. Different types of plasma-arc generators may be used for materials processing. These include DC (direct current) and AC (alternating current) plasma generators. At present, DC plasma generators are most widely used for technological applications.

Depending on the particular application and required performance, different basic designs of plasma torches and electrode materials are used. In tubular electrodes, to reduce erosion and thus increase electrode life, arc rotation within the electrodes is maintained either by vortex-stabilizing aerodynamic flow induced by tangential injection of pressurized gas between the electrodes or by external rotating magnetic field or a combination of both. Rapid rotation or movement of the arc attachment points on the electrode surface spreads out the heat load.

Free- and fixed-length-arc basic designs are shown in Figure 2-3 and Figure 2-4 respectively.

The free-length-arc plasma torch consists of two tubular electrodes isolated from each other by an insulator in the region of the plenum chamber into which gas is injected tangentially.

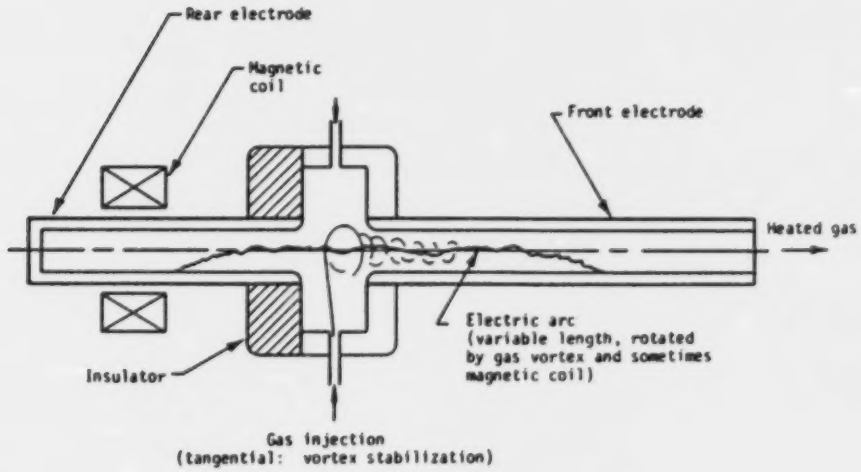


Figure 2-3 Free-Length-Arc Plasma Generator

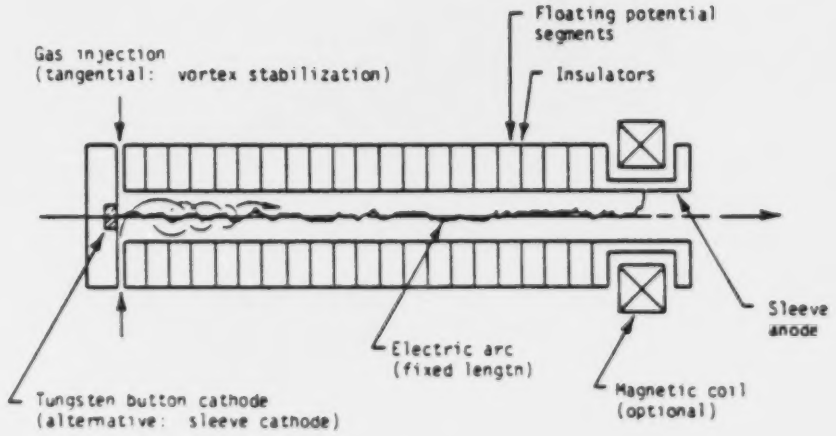


Figure 2-4 Fixed-Length-Arc Plasma Generator

The free-length-arc plasma generators are simple and well suited for high pressure applications, but have limited enthalpy capability as compared to a fixed-length-arc basic design.

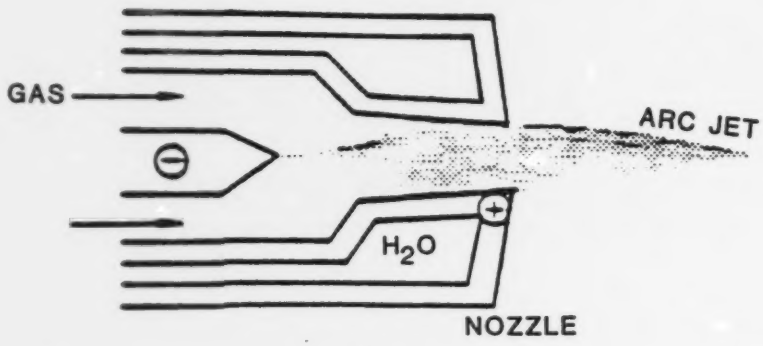
In the fixed-length, segmented-constrictor-arc design, presented in Figure 2-4, the insulated segmented column between anode and cathode stretches the arc beyond its natural (free) length and forces the arc to run at a preselected constant length. In the free-length-arc generator, when the gas between the arc and the wall is hot enough, the lowest resistance electrical path exists and no more energy may be added to the gas, even if the electrode channel extends beyond the point of the arc attachment. In the fixed-length arc, the energy addition continues up to the point where the anode is located. Thus, a higher enthalpy may be generated [10].

Depending on the application, either cold- or hot-type cathodes are used in plasma generators. The cold-type cathode is based on field emission as a source of electrons, compared to thermal emission used in hot electrodes.

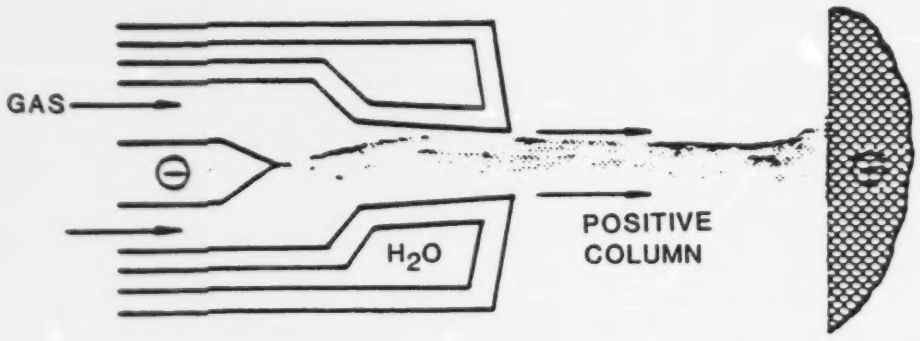
Tungsten, thoriated tungsten and barium-calcium-aluminate or lanthanum-doped tungsten are used as cathode materials. Hot cathodes are limited to the low to moderate pressure applications.

Copper alloys, including copper-tungsten are applied for cold cathodes.

Plasma generators are commonly used in two modes of operation: non-transferred-arc (Figure 2-5a) and transferred-arc (Figure 2-5b).



a) Non-Transferred-Arc Plasma Torch



b) Transferred-Arc Plasma Torch

Figure 2-5 Non-Transferred- and Transferred-Arc Plasma Generators

For applications where more power must be coupled into the materials to be treated, the transferred-arc mode of operation is usually applied. In this case, the material becomes the anode. The transferred-arc mode of operation permits longer plasma arcs with higher currents achievable at lower voltages as compared to non-transferred-arc plasma generators. Thus higher enthalpy or energy density and more efficient power utilization into the material may be achieved in a transferred-arc mode of operation [11]. Therefore, the transferred-arc mode of operation is applicable to plasma reactors (furnaces) where high temperature heating and melting of materials is required. Non-transferred-arc plasma generators (torches) are used preferably for "in-flight" reactive processes.

In plasma generators used as heaters, inert gases are employed as plasma generating (plasmagen) gas. Where reactive environment is required, synthesis or natural gas, hydrogen, etc., is applied (in combination with inert gas or without).

A plasma system comprises the following integrated sub-systems in addition to a plasma generator:

- power supply
- gas supply
- cooling water
- control and instrumentation

A power supply is required to provide electrical energy to the plasma generator. Power supply characteristics must be closely matched to those of the plasma torch for optimum performance in an industrial environment. As already noted, plasma torches may be operated on AC or DC power; and power supplies must have sufficiently high voltage capability to provide sparkover in the inter-electrode gap to ensure process continuity. For DC plasma generators, DC power supply with inductor ballast or thyristor control may be used. Schematics of DC plasma power supply with thyristor control is shown in Figure 2-6 [12].

A gas supply system will be dictated by the specific process requirements; utility sources or recycle process streams may be used. In the latter case, dust-laden streams must be scrubbed before compression thus providing a dry, particulate-free gas stream to the plasma generator. If plant compressed air or steam is used, appropriate moisture separation and particle removal devices must be installed. Other gas system components include: pressure, temperature and flow sensors; interlocks; flow control devices; appropriate isolation and shut-off valves, etc.

Cooling-water system. Plasma installations for plant environments generally require closed-loop coolant systems for removal of heat lost to the plasma torch walls. Local internal heat flux along the electrodes can reach levels of 1.94 to 5.16 kW/cm^2, thus high coolant velocities of about 10 or 30 m/s are required [13]. Circulating pumps with pressures of 1.5 to 3.0 MPa total dynamic head are typically used. Other coolant system components include conventional valving, strainers, heat exchangers, and surge reservoirs, as well as flow and temperature sensors for heat balance analysis and control purposes.

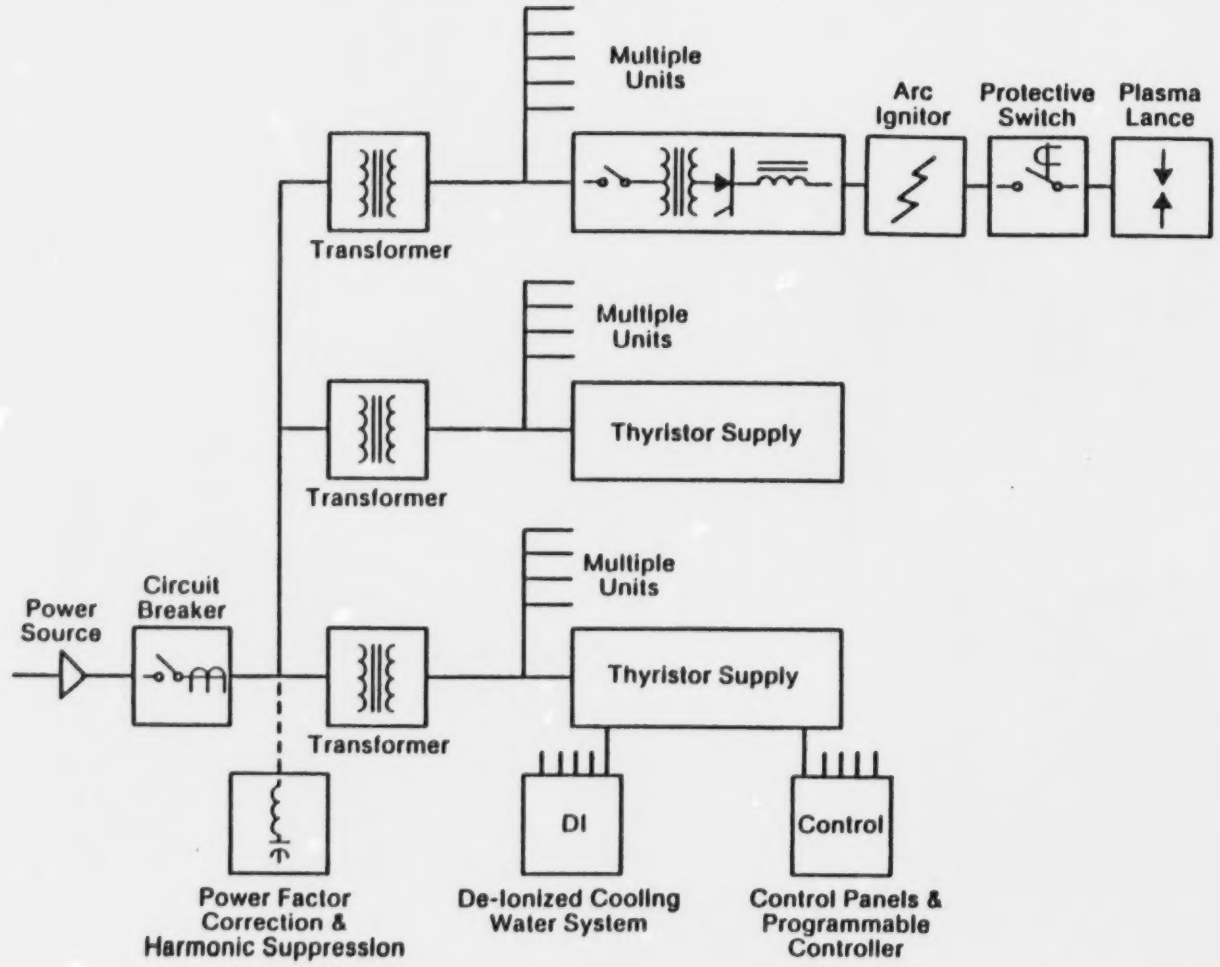


Figure 2-6 Plasma Power Supply Schematic

A typical **control and instrumentation system** for the plasma power supply consists of a console containing alarm indicator, meter readouts, pushbutton controls and associated relays. The design of the control system includes an interlock scheme for start-up and shutdown which permits, under selected conditions, certain primary sensors to both lock out and trip the power control breaker. The control system should be mechanically interlocked with the plasma generator (torch) and associated power devices, thus preventing improper sequence of equipment operation or personnel access to high voltage equipment while energized.

Brief descriptions of commercial (or demonstrated at the pilot-level) plasma generators (torches) of Westinghouse Electric and Plasma Energy Corporations (U.S.A.), Aerospatiale (France), SKF Steel Engineering (Sweden), and Huels Chemical Company (F.R.G.) follow:

2.2.1 Westinghouse Plasma Generators

The Westinghouse Electric Corporation, U.S.A., has developed and is manufacturing a series of industrial plasma generators (torches), model MARC, power input from 75 kW up to 10 MW. A cross-section of the Westinghouse plasma generator is shown in Figure 2-7. This plasma generator consists of a closely-spaced pair of tubular, water-cooled copper electrodes within which an electric-arc discharge is magnetically rotated at high speeds. In operation, a process gas is injected through the gap between the electrodes which are spaced approximately 1 mm apart. A source of 4-kV electric power is sufficient to provide sparkover in the electrode gap, initiating the arc discharge, which is immediately blown to the interior of the arc chamber by the incoming process gas. There the arc is rotated at speeds up to 3000 r/s by interaction of the arc current (up to 2000 A) with DC magnetic field set up by internally mounted solenoid coils. The

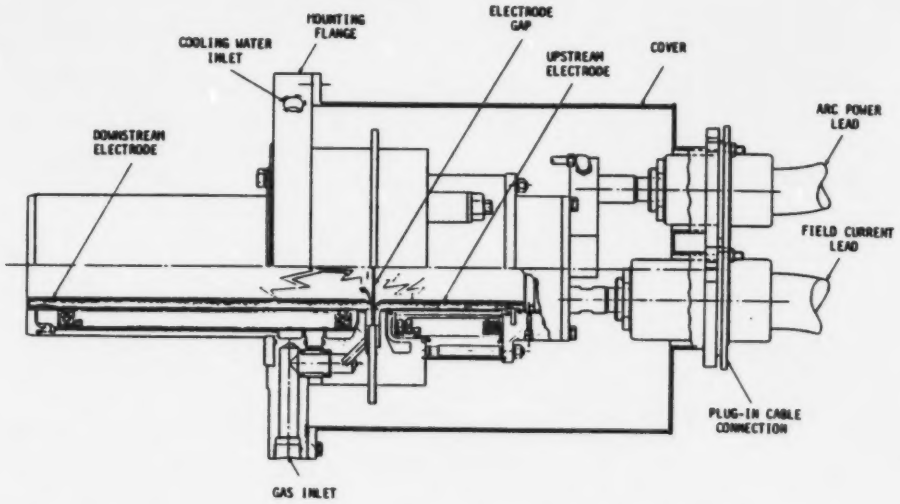


Figure 2-7 Cross-Section of Westinghouse Plasma Generator

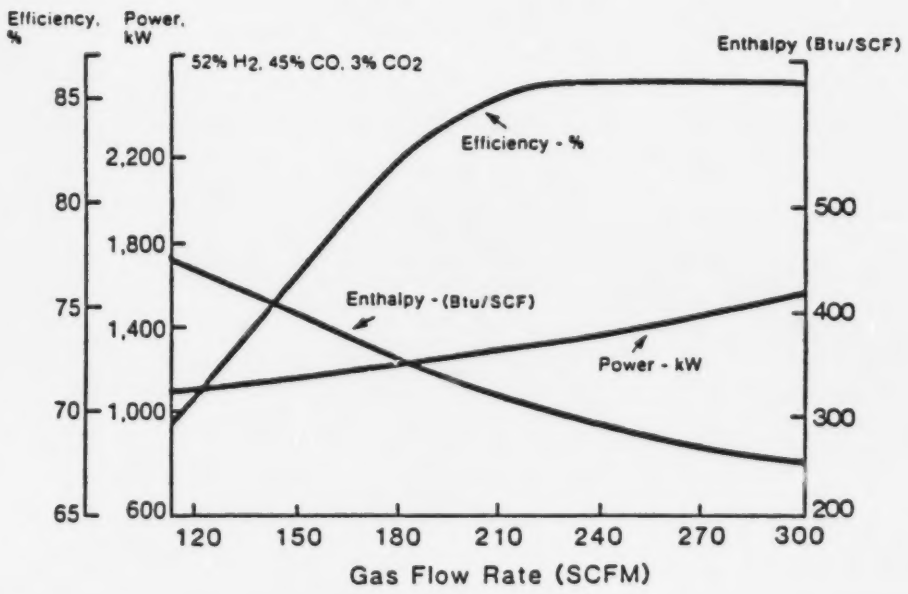


Figure 2-8 Westinghouse Plasma Generator Performance Characteristics

Table 2-1 Characteristics of Westinghouse Plasma Torches

Model	Power* MW	Typical Gas Flow** m^3/h	Cooling Water Flow m^3/h
MARC 3	0.075 - 0.15	10 - 20	4.5
MARC 11	0.5 - 2	100 - 425	16
MARC 31	1 - 3	300 - 765	25
MARC 100	2 - 10	600 - 2000	25 - 50

Efficiency: 70% to 90%

Enthalpy : 3 to 7 kWh/m^3 (300 to 700 $\frac{Btu}{scf}$)

* Arc power rating will depend on gas composition

** Gas Flow will depend on gas composition

Source: Westinghouse, "Industrial Plasma Systems", 85th Annual Meeting, Canadian Institute of Mining and Metallurgy, Winnipeg, April 17th, 1983.

sparkover is self-starting when energized, and self-stabilizing during operation. Any gas can be used in the Westinghouse plasma torches, whether oxidizing, reducing or inert. Process temperatures can be controlled by varying the arc current independently of the gas feedstock flow rate, and thereby optimized for high efficiency. Depending on application, DC or AC power supply may be used. An example of Westinghouse DC plasma torch performance characteristics are presented in Figure 2-8 [12]. Characteristics of the Westinghouse plasma torches, model MARC are summarized in Table 2-1.

2.2.2 Aerospatiale Plasma Generators

Aerospatiale, France has developed DC plasma generators (torches), for industrial applications, in the power range of 2 to 10 MW , using compressed air (100 kPa to 2 MPa) as a plasma gas. The torch is designed for a current below 1000 A and enthalpy between 0.5 to 4.0 kWh/kg when air is used as plasma gas.

The Aerospatiale industrial plasma torch development is based on over 20 years of the company's experience with high power DC plasma heaters employed at the Aerospatiale testing facility for studying the behaviour of re-entry materials at very high temperature in the course of space programs.

The schematic of Aerospatiale industrial plasma generators (torches) is shown in Figure 2-9. The torch consists of two tubular coaxial water-cooled copper electrodes between which pressurized air is injected tangentially. Arc rotation along the electrodes is maintained by combined action of vortex-stabilizing aerodynamic gas flow and external rotating magnetic field. A starting electrode is used to initiate the arc between the main electrodes. Testing of the 2.2-MW plasma torch at 900 A and 2400 V using air as a plasma gas allowed continuous low intensity

operation (enthalpy 2.4 kWh/kg) for more than 200 hours. The time required for replacement of electrodes is 10 minutes according to information provided by Aerospatiale. Used electrodes may be remachined [14].

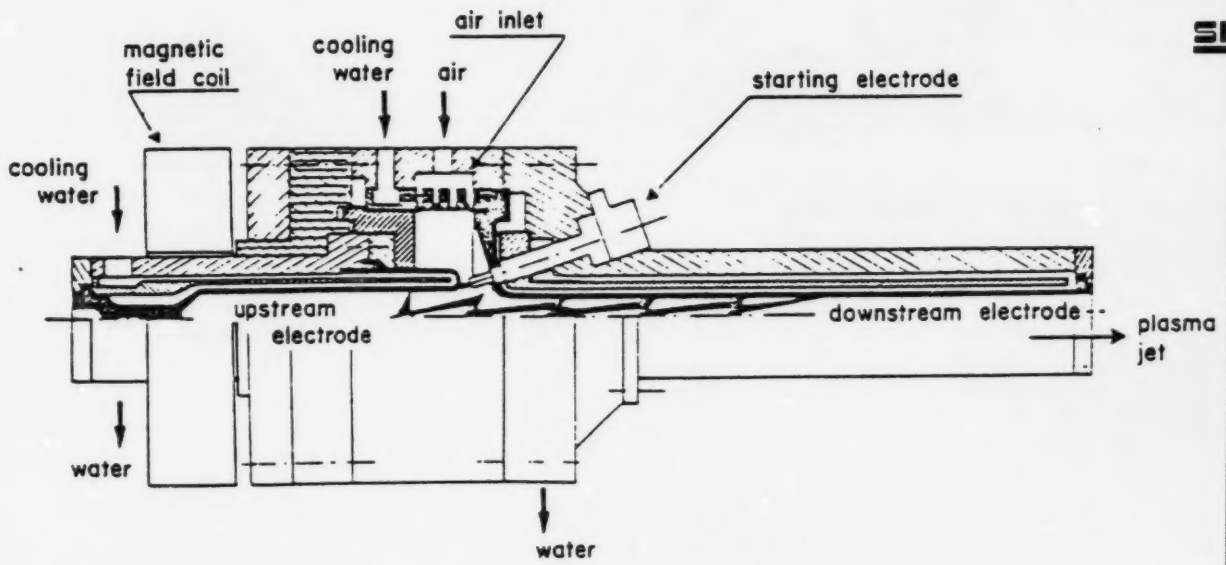


Figure 2-9 Cross-Section of Aerospatiale Plasma Generator

The main characteristics of the plasma torches which may be at present supplied by Aerospatiale [14] are as follows:

Power:	2 to 10 MW DC
Current:	1000 A max.
Voltage:	3000 V max.
Gas:	Air
Pressure:	0.1 to 2.0 MPa
Gas flow:	200 to 1200 Nm^3/h
Efficiency:	90%
Enthalpy:	0.5 to 4.0 kWh/kg

Guaranteed electrode life - 400 hours (for continuous operation with air as a plasma gas).

For demonstration of plasma technology in various industries, Aerospatiale has recently developed jointly with Jeumont-Schneider and Electricité de France, a Mobile Plasma Unit (MPU) consisting of a 2.1-MW plasma torch, electric power supply, gas supply, water cooling and control systems. The complete MPU may be transported in four standard containers. In January 1985, the MPU was tested in a commercial blast furnace for iron production at Uckange plant located in Lorraine, France (see details in Chapter 3).

2.2.3 Plasma Energy Corporation Generators

Plasma Energy Corporation (PEC), U.S.A. has developed a series of industrial DC long-column plasma generators (torches), series PT in the power range from 50 to 6000 kW (50 kW, 150 kW, 1000 kW, 1500 kW, 3500 kW, 4500 kW and 6000 kW). The plasma system also included electric power supply, gas system, control panel, closed-loop water-cooling system and plasma starter. The torches

manufactured by PEC may be supplied for transferred or non-transferred operation. Also, "field-convertible" from transferred to non-transferred operation and vice-versa, as well as "hybrid" plasma arc torches, are available. The hybrid plasma torch can operate in either mode, transferred or non-transferred, depending on how far the torch is positioned from the external electrode, scrap or melt. For the hybrid type of PEC torch, however, optimum characteristics will not be achieved in either configuration [15]. The schematics of transferred and non-transferred PEC plasma torches are shown in Figure 2-10.

The cross-section of the PEC transferred-arc plasma generator is shown in Figure 2-11. Contrary to a conventional electrode arrangement, the rear electrode is positive, while the front electrode is negative. In front of the rear electrode (i.e., anode), is located the collimator which functions as the other electrode during the start and then collimates or concentrates the plasma-arc column as it emerges from the torch. Anode and collimator are separated by the main insulator. A metallic vortex generator is located within the main insulator. Plasma gas is introduced through the vortex generator and the vortex flow produced creates a low pressure region at the axis of the electrodes. The plasma arc column is stabilized in this low pressure region. The electrode, collimator, main insulator and vortex generator are enclosed in the shroud.

PEC reported [15] that water-cooled alloyed copper electrodes can be used for continuous operation up to 400 hours. The exchange of electrodes takes 15 to 20 minutes. Electrode erosion rates as low as 2 to 10 milligrams per hour for a 100-kW torch has been demonstrated. An inert gas was used in this test. The efficiency of the torch is up to 90%.

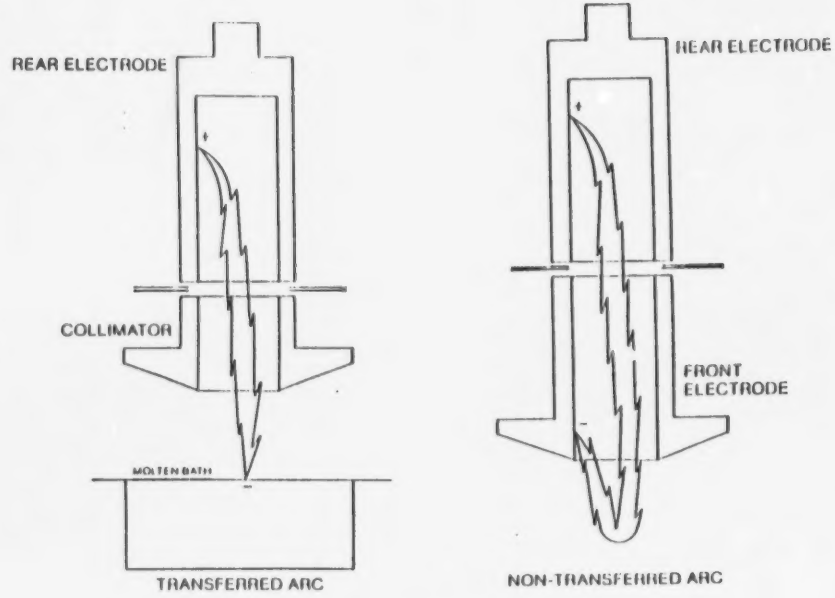


Figure 2-10 PEC Plasma Torches

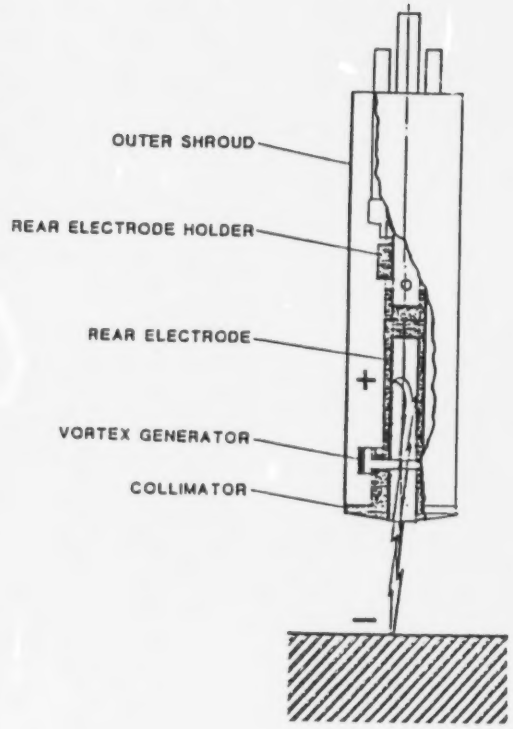


Figure 2-11 Cross-Section of PEC Transferred-Arc Plasma Generators

A number of technological applications of PEC plasma torches have been reported [15] (some will be discussed in Chapter 4). However, for most of the applications, no details are available due to the confidential character of the work being carried out by PEC jointly with the industrial companies concerned.

2.2.4 SKF Plasma Generators

SKF Steel Engineering AB, Sweden has developed and demonstrated 3-MW and 6-MW DC plasma generators in its pilot-plant at Hofors.

These plasma generators have been developed as an integral part of SKF development of several metallurgical processes aimed at substitution of conventional equipment (e.g., blast furnaces for production of pig-iron, equipment for production of iron through direct iron-ore reduction) and based on the SKF concept of using a shaft filled with coke as a reaction vessel in combination with plasma generators. The processes have been called correspondingly PLASMASMELT (for direct smelting of iron-ore), PLASMARED (for direct reduction of iron ore), PLASMACHROME (for production of ferrochrome), etc. The description and discussion of some of these processes are presented in Chapters 3 and 4.

Since the early 1970s, SKF Steel Engineering has been developing plasma technology on the basis of plasma torches supplied by other companies such as the 0.5-MW DC plasma torch from the Swedish Company, AGA; then, the 1.5-MW AC plasma torch supplied by Westinghouse, replaced later by 2-MW DC plasma torches from Westinghouse, model MARC 11 discussed earlier. Also, the 1-MW fixed-length DC plasma torch of ACUREX, U.S.A. was used for basic parametric tests in the SKF Steel pilot-plant. Based on test

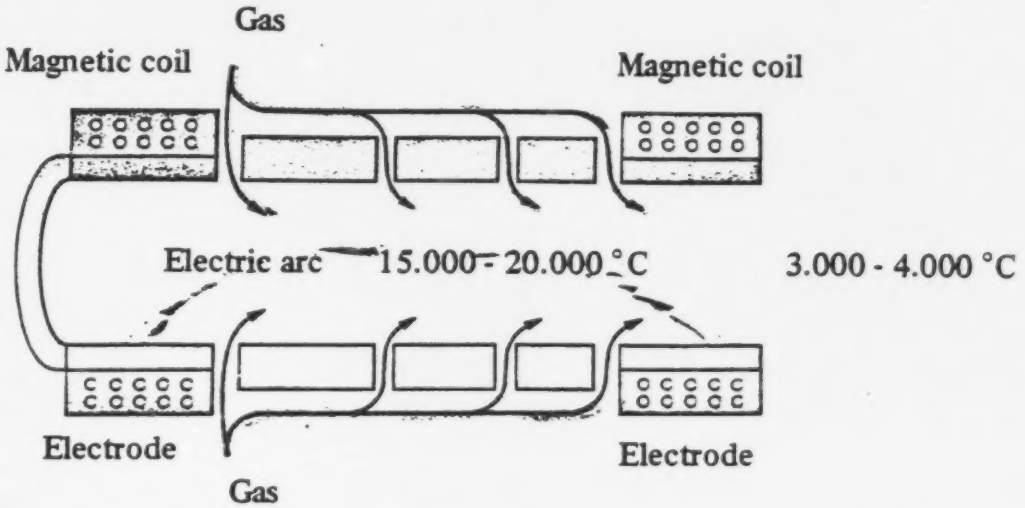


Figure 2-12 SKF Plasma Generator

results obtained, the plasma generator specification requirements for application in plasma metallurgical processes have been established [16].

The program on development of SKF plasma generators started in 1980. In July 1983, three 3-MW plasma generators developed by SKF were already operational. A 6-MW SKF plasma generator was in operation at the SKF PLASMARED pilot plant. In April 1984, three other 6-MW plasma generators were installed at PLASMADUST, a commercial plant commissioned at Landskrona, Sweden. The plant is designed for recovery of metals (zinc, lead, chromium, iron) from baghouse dust of electric-arc furnaces [17]. (See details in Chapter 4).

The principle of commercial 3-MW and 6-MW SKF plasma generators is shown in Figure 2-12. These are fixed-length, non-transferred-arc, segmented DC plasma generators (torches). External magnetic coils are used for arc stabilization. The plasma generator consists of two water-cooled copper electrodes separated by tubular segments. The segments are water-cooled and electrically insulated from each other and from the electrodes. Recycle process gas is used usually as plasma gas. The gas is introduced in the gaps between the segments.

The characteristics of the SKF commercial 6-MW plasma generator (torch) are summarized below:

Electric power:	6 MW DC
Current:	1650 A
Enthalpy:	4 to 4.5 kWh/m^3 (400 to 450 Btu/scf)
(Maximum):	8.0 kWh/m^3 (800 Btu/scf)
Efficiency:	83% to 85%
Plasma gas flowrate:	1500 m^3/h (883 scfm)
Electrode life:	200 hours
Electrode cleaning:	50 to 100 hours (depending on gas composition)
Cooling-water requirements:	16 to 22 m^3/h

Overall dimensions of 6-MW plasma-generating unit:

- Length: 1.2
- Height: 5 m
- Width : 6 m

Weight: 500 kg

2.2.5 Huels Plasma Generator - Reactor

Huels Chemical Company (Hüls Chemische Werke), F.R.G., has been operating a commercial plasma reactor for production of acetylene from natural gas or refinery hydrocarbon gases since 1939.

The schematic of a 8.5 to 10-MW Huels plasma torch is presented in Figure 2-13. It is a free-length, aerodynamically stabilized, non-transferred-arc DC plasma reactor. The hydrocarbon gas to be processed enters the reaction zone tangentially through a turbulence swirl chamber (R), where it is given a vortex motion before entering the anode pipe (A). The swirling motion of the downward-flowing gas stream stabilizes the arc (L) which is struck between the cathode (C) and anode (A), grounded at (E). Both electrodes are hollow and water-cooled. The striking points of the arc in the anode and/or cathode may be moved upward or downward as required. Huels calls it "elastically suspended arc". All parts of the reactor with the exception of insulator (J) are made of iron. During start-up, the arc is struck with the ignition device (Z). The reactor operates at a capacity of 8.5 MW, 7000 V, 1150 A, DC. The average length of arc is 100 cm. The arc extends 40 to 50 cm into the anode pipe [18].

The hot reactor gas (about 1750 K) containing mostly acetylene and hydrogen is pre-quenched with liquid hydrocarbons (C_2 or higher) at (D), about 20 cm below the arc to use the heat for partial cracking of these liquid hydrocarbons to ethylene. The emerging gas containing acetylene, ethylene and hydrogen is water-quenched at (W) to cool the gas to about 450 K. (For details on production of acetylene using Huels plasma torch reactor see Chapter 6).

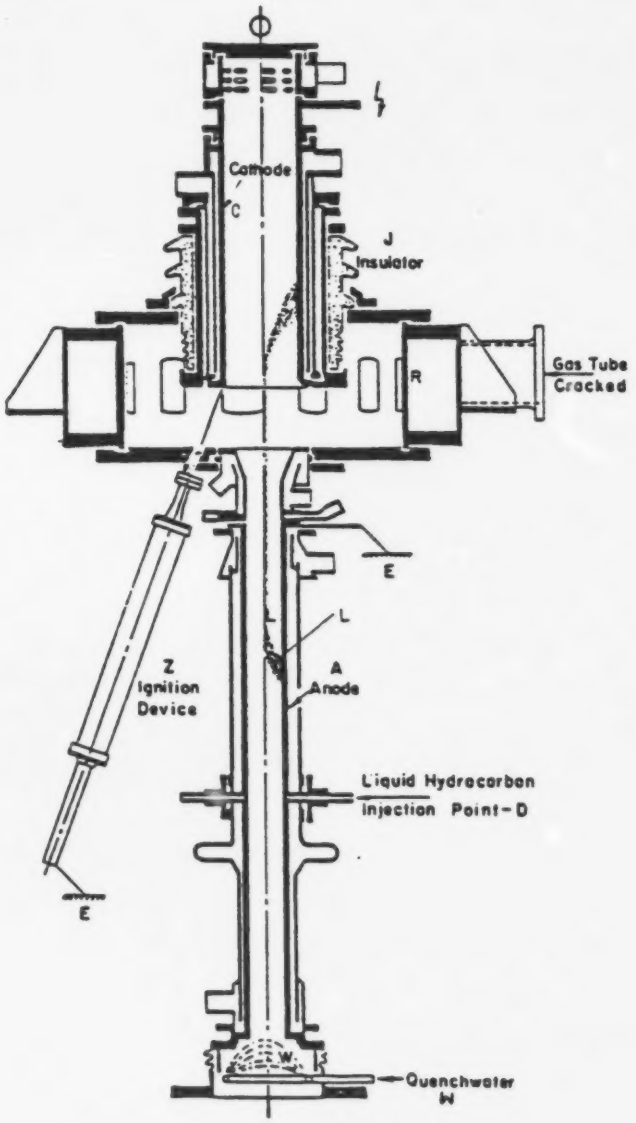


Figure 2-13 Huels Plasma Generator - Reactor

The comparative characteristics of plasma systems based on plasma generators (torches) described above is shown in Table 2-2.

In Canada several manufacturers are capable of supplying the components of plasma generating systems. In particular, negotiations on the licensing agreement are in progress between the Canadian company, Volcano Inc., Quebec and Aerospatiale, France [19]. Supply of complete industrial plasma systems (including plasma torch, electric power, gas, cooling and control systems) is considered by Volcano Inc.

2.3 PLASMA REACTORS (FURNACES)

Plasma reactors (furnaces) used for gas-particle treatment may be subdivided into two classes [21]:

- dispersed-particle reactors
- bulk phase reactors.

Dispersed-particle reactors are plasma reactors where the particles are injected and treated with the hot plasma gas flames. The contact time that the solid particles remain in the plasma environment is usually short (in the order of milliseconds). In some cases, such contact time is only sufficient for melting and other changes of particles to occur (e.g., spheroidization), but is too short for chemical reaction. Because of sharp variation in temperature and velocity profiles in the flame, treatment is not uniform.

Several plasma reactor designs are being explored to extend the reaction contact time of the particles. One of the approaches is to have an extended-arc volume through which the solid particles are passed [22]. Another reactor design includes precessing at

Table 2-2 Comparative Characteristics of Plasma Systems

	Westinghouse	Aerospatiale	SKF	Huels	PEC
Electric Power, MW	0.15-10	2 - 10	6	8.5	0.05 - 6
Gas used	Air, Ar, N_2 CH_4, process gas	Air	Process gas	Hydrocarbon gases	Ar, N_2, air process gas
Gas Flow Rate, m^3/h	10 - 2000	200 - 1200	1500	293*	N/A
Enthalpy, kWh/m^3	3 - 7	0.5 - 4	4 - 4.5 (max. 8)	3.4*	N/A
Efficiency**, %	70 - 90	85 - 90	83 - 85	88	70 - 90
Electrode life, h	200 - 400	200 - 400	200	Cathode: 800 Anode : 150	200 - 400
Cooling-Water Flow Rate, m^3/h	4.5 - 50	15 - 30	16 - 22	15 - 20	N/A
Investment***, $/kW	350	400	N/A	66	350

* For Huels plasma generator-reactor, gas flow rate and enthalpy are presented for feedstock hydrocarbon gas.

** Does not include efficiency of rectifier. Also efficiency quoted is from electrode to gas, but does not include transfer from hot gas to working medium.

*** Investment per kW of installed capacity depends on plasma generator rating. Investment ($/kW) for Westinghouse and Aerospatiale Systems is presented for a generator rating of 2 MW; for PEC plasma system, 1.5 MW [20]; and for Huels plasma system, 8.5 MW.

sufficient speed (e.g., 500 r/m) transferred-arc plasma generator. The arc struck between precessing and stationary electrodes forms a conical hot zone into which the particles are injected [23]. A concept of falling-film plasma reactor has also been intensively investigated [24]. In the falling-film plasma reactor, solid particles are injected tangentially in a stream of a carrier gas and are aerodynamically centrifuged into the reactor inner walls to form a film that flows down the walls. As a result, the residence time of the reactants in the falling-film within the hot-plasma environment may be increased up to several minutes [25].

Bulk-phase plasma reactors (furnaces) are basically transferred or non-transferred arc plasma heaters used for melting, remelting and refining of scrap, alloys, primary metals and other materials placed in a "bulk-phase" at the bottom of the reactor. If "bulk-phase" material is electrically conductive, it is often used as a part of the plasma arc electric circuit in order to achieve additional "bulk heating" of the material.

A wide variety of plasma reactors (furnaces) have been developed and demonstrated on a semi-commercial- or commercial-scale worldwide during the last decade. Some of these plasma reactors (furnaces) are briefly presented below.

CANADA

As already mentioned in Chapter 1, two plasma reactors (furnaces) have been developed in Canada: the transferred-arc DC plasma reactor of Noranda and the extended-arc AC plasma reactor of the University of Toronto.

2.3.1 PLASMACAN Reactor (Furnace)

The transferred-arc DC plasma reactor developed at Noranda Research Centre, Pointe Claire, Québec now registered under the trade name PLASMACAN is shown in Figure 2-14. The cathode design is shown in Figure 2-15.

A gas-stabilized arc is struck between the non-consumable cathode and the molten pool of reactants in the furnace hearth which is in contact with the anode located in the bottom of the furnace. The plasma column passes down a water-cooled reaction sleeve or cyclone which surrounds a substantial length of the arc column. Reactants are injected tangentially into the sleeve at sufficiently high velocity to form a uniform covering on the inner wall of the reaction sleeve.

Radiant heat from the plasma column melts the reactants to form a falling film of molten material flowing down the inner wall of the sleeve. The molten material then drops into the furnace hearth where the reaction is completed in the molten bath heated by electron recombination on the surface of the anodic molten metal. The falling film of molten material absorbs radiation heat. Therefore, no water cooling of the reactor is necessary. A skull of solidified metal is formed against the reactor refractory which protects the refractory. In addition to cooling water, the cold plasmagen gas is used to cool the cathode assembly. No cooling of the anode is required if anode plate has an appropriate surface area and a heel of molten metal is left at all times at the bottom of the reactor [26]. Whatever additional residence time is required may be provided in the molten bath before the product is tapped out.

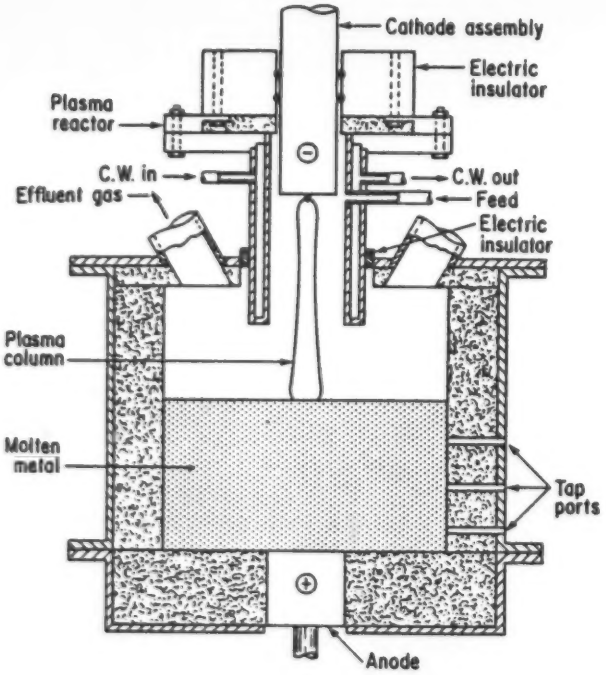


Figure 2-14 Noranda Transferred-Arc Plasma Reactor

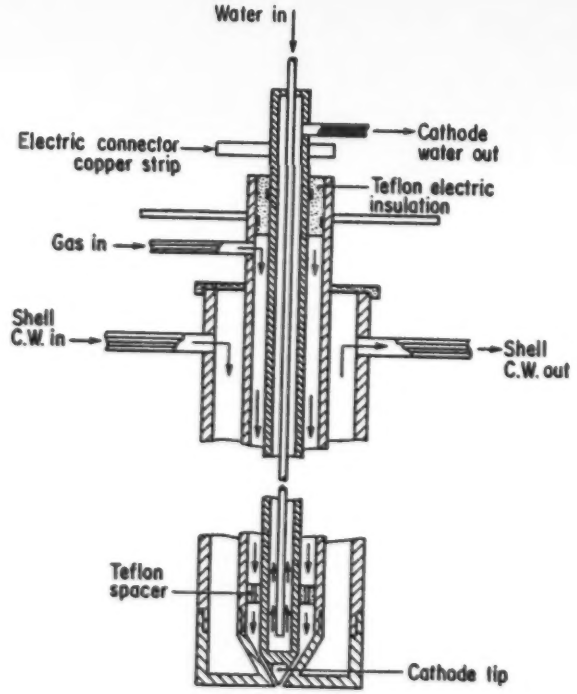


Figure 2-15 Cathode Design of Noranda Transferred-Arc Plasma Reactor

Several small-scale (up to 125 kW) versions of this furnace have been tested at Noranda. Studies on operating characteristics and engineering applications of transferred-arcs in relation to the Noranda configuration of plasma reactor have been carried out at McGill University [27]. As already mentioned, the reactor was patented by W.H. Gauvin and G.R. Kubanek [2]. In 1981-1982, the Noranda patents were assigned to IREQ (Institut de Recherche d'Hydro-Québec) which in turn gave a world-wide licence (except for Canada) to Davy McKee U.K. Since then, Davy McKee Research and Development in Stockton-on-Tees, England, constructed a plasma reactor based on the Noranda configuration, 1-MW nominal capacity and tested the reactor at power input up to 250 kW. Some test results obtained on direct iron-ore smelting are discussed in Chapter 3. Another 250-kW PLASMACAN plasma reactor was designed and installed at the University of Sherbrooke's Plasma Centre for testing on various industrial applications [3]. The reactor is presently undergoing trial operations.

2.3.2 University of Toronto Plasma Reactor (Furnace)

The extended-arc flash AC plasma reactor (EAFR) developed at the University of Toronto operates on 3-phase AC. The power supply may be the conventional frequency alternating current (60 Hz). The plasma arc is struck between three inclined hollow graphite electrodes through the bore of which the plasmagen gas (Ar, Ar + H_2 or CO) is fed. (See Figure 2-16.) The feed (e.g., metal oxide ore, slag and reductant), preheated in a rotary preheater with the effluent gases, falls by gravity through the flash column where it is pretreated in a countercurrent flow of hot reactive gases evolved in the process before passing through the arc. The liquid metal and slag are collected in the hearth zone and removed periodically through the tap ports.

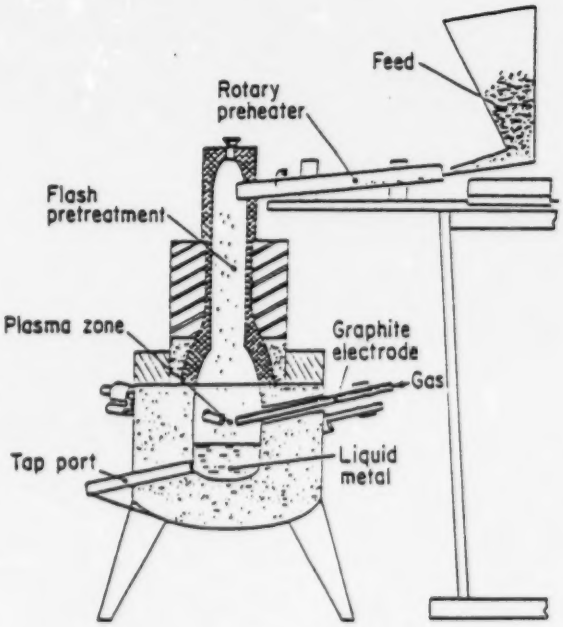


Figure 2-16 University of Toronto Plasma Reactor

The temperature distribution within the plasma zone created between the electrodes is relatively uniform. The flow rate of plasmagen gas required is comparatively low. The thermal conditions within the hearth zone can be controlled by adjustment of the flow rate and composition of the gas injected through the electrodes. There is no need for internal water-cooling of the electrodes [28]. Application, however, of consumable graphite electrodes may be detrimental for certain applications since it may create carbon contamination of the product. It is also necessary to agglomerate or pelletize the feed when treating very fine particles.

As mentioned earlier, the EAFR furnace was extensively tested at a relatively low power level (up to 100 kW) for iron-ore smelting, treatment of steel plant waste oxides, production of ferro-alloys, etc., [29]. A 1-MW plasma demonstration facility based on EAFR design has been built and is undergoing preliminary trials at the Ontario Research Foundation, Mississauga, Ontario [7].

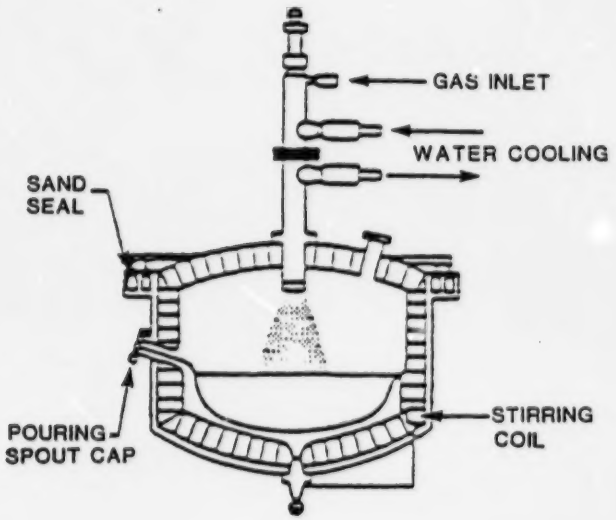


Figure 2-17 Linde Plasmarc Furnace

U.S.A.

2.3.3 Linde Plasmarc Furnace

The thermal plasma furnace at the Linde division of Union Carbide, U.S.A. was one of the first to be used for steel melting in the early 1960s [30]. The schematic of the Linde Plasmarc furnace is shown in Figure 2-17. This is a DC plasma furnace, operated at a maximum capacity up to 900 kg in the transferred-arc mode under an inert gas (argon) environment. A water-cooled cathode is located in the furnace roof. The furnace lining at the bottom was fitted with a water-cooled copper anode. The electrodes are connected to the main bus bars of the power source through flexible water-cooled cables.

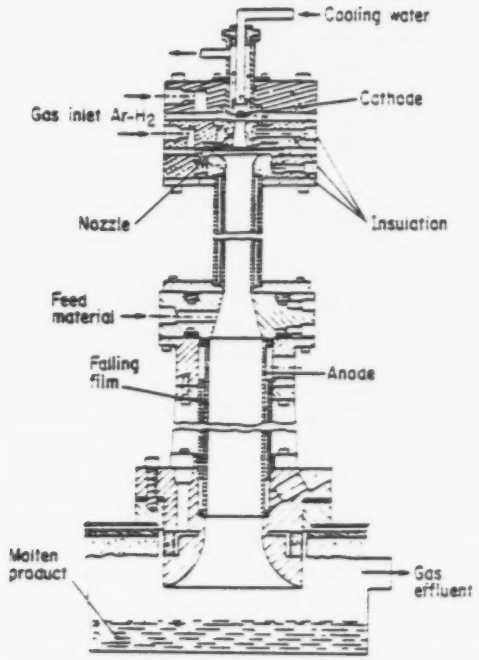


Figure 2-18 Bethlehem Steel Falling-Film Plasma Reactor

Over 100 hours of operation was reported at current levels exceeding 1000 A. The operating voltage was relatively low (less than 100 V). Rapid wear of the bottom electrode, water leakage from the plasma source, and high erosion of the refractory lining caused by the abrasive action of magnetically mixed molten steel were identified as problem areas.

2.3.4 Bethlehem Steel Falling-Film Plasma Reactor

This reactor was developed and demonstrated by Bethlehem Steel at 100- and 500-kW levels for production of ferrovanadium, 100-kW and 1-MW levels for direct iron-ore smelting [24, 31]. The reactor is shown in Figure 2-18. The arc is struck between the water-cooled tungsten cathode and the vertical hollow

water-cooled copper anode insulated from the cathode. The arc is stabilized by a vortex gas flow between the cathode and the anode. The reactant feed particles (e.g., iron oxide fines) pneumatically injected between cathode and anode are aerodynamically centrifuged onto the reactor inner walls to form a film which flows down the walls. When the arc is struck, sufficient heat is available to melt these particles into a falling-film of material on the wall of the anode. This film becomes part of the anode. The stabilizing gas is usually a mixture of hydrogen and natural gas at a ratio (H_2/CH_4) of 2 to 2.5, injected at the cathode level. The molten metal in the bottom crucible is heated only by convection from the effluent gases.

The main advantage of the process is claimed to be the relatively long residence times, improved heat transfer and direct contact of the metal oxide and reductant resulting in higher metal yields. Some details on the demonstration of this reactor for direct iron-ore smelting are given in Chapter 3, for ferrovanadium production, in Chapter 4.

2.3.5 Plasma Energy Corporation (PEC) Plasma Reactors

PEC has been developing and demonstrating in several industrial sectors plasma furnaces based on PEC plasma generators described earlier (see Section 2.2, Plasma generators). These include plasma furnaces for iron-ore smelting, remelting, reductant gas generation by plasma pyrolysis of solid carbonaceous materials and others [32].

A schematic of the PEC rotating plasma furnace considered for various applications, in particular fused-silica production, is presented in Figure 2-19. This is an inclined rotary-kiln-type

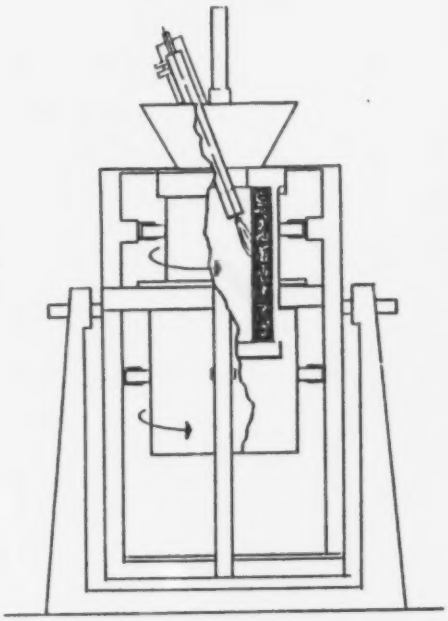


Figure 2-19 PEC Rotating Plasma Furnace

furnace in which a non-transferred plasma-arc torch may be adjusted at various angles and depth. In this furnace, no refractory lining is used. Instead, a pre-set thickness of the material to be fused, e.g., silicates and aluminates for cement manufacture, is formed. The shape of the furnace is dictated by the flow characteristics of the fused material [32].

Some other U.S. companies are known at present to use thermal plasma reactors on a commercial scale, e.g., the Ferro Corporation, Bow, New Hampshire, formerly TAFA/IONARC, for processing zircon, and Plasma Materials Inc., (PMI) to spheroidize particles of magnetic iron oxide for further use in photocopy machines having a magnetic brush developer system.

JAPAN

The most notable contributions to the development and application of plasma technology in Japan have been made by the Daido Steel Company, Nagoya which developed and is using commercial-scale melting/remelting plasma furnaces. Also, at Nippon Stainless Steel Company, Japan, a 2.4-MW plasma beam furnace (including six 400-kW plasma torches in parallel) for titanium production is in operation [33].

2.3.6 Daido Steel Plasma Furnaces

The Daido Steel Plasma Induction Furnace (PIF) is shown in Figure 2-20. In the PIF furnace, combined plasma and induction heating is used for melting and refining of steels and alloys in an inert (argon) atmosphere as an alternative to the vacuum induction furnace (VIF). The pilot PIF for process development had a capacity of 0.5 tonne. A 2-tonne commercial PIF has been in operation since 1975; a 5-tonne PIF furnace is being designed. The 2-tonne PIF is equipped with a 600-kW induction heating coil, 400-kW transferred-arc plasma heater with a tungsten cathode (maximum current 3000 A at 150 V) and a 200-kW induction stirring coil. About 80 per cent of the total input energy for metal melting is provided by induction coils. The remaining 20 per cent of heat is provided by the plasma heater which is used during the refining stages for melting of slag and providing melt surface temperatures which are about 200° to 300°C higher than that of the bulk metal. Alloys containing reactive metals such as aluminium, titanium, niobium and zirconium, high vapor pressure elements, e.g., manganese and copper, heat resistant steels and alloys can be melted in the Daido PIF. Some comparative data on the vacuum induction furnace (VIF) and the PIF are summarized in Table 2-3.

TABLE 2-3 Comparison of VIF and PIF Systems [30]

Characteristic	VIF	PIF
Volatilization	High	Low
Mechanical property	Good	Good
Workability	Excellent	Good
Yield (melting), %	98	98.9
Product yield (total), %	75	85
Melting cost (index)	100	59
Oxygen, ppm	5-15	8-25
Nitrogen, ppm	10-30	10-50
Hydrogen, ppm	1	2-5
Desulphurization, %	10	50-85
Decarburization, %	90	70

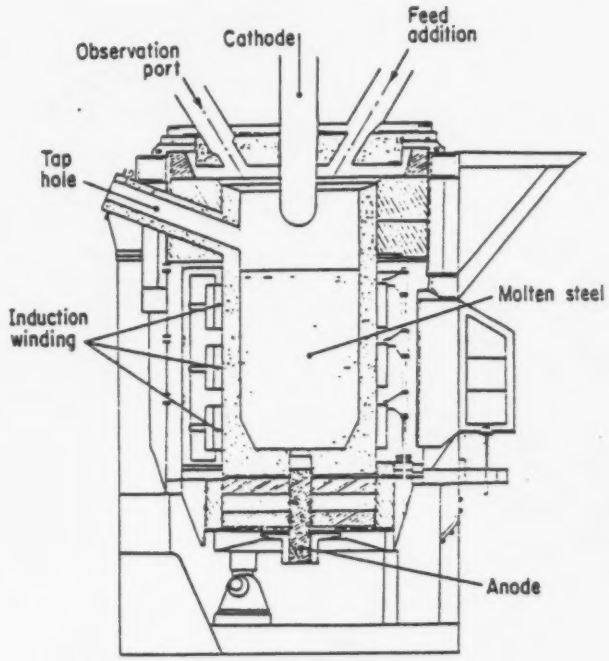


Figure 2-20 Daido Steel Plasma Induction Furnace

Another plasma development at Daido is the so-called plasma progressive casting (PPC) reactor. PPC reactors are used for continuous melting and casting of refractory metals, alloys, etc. [30].

GERMAN DEMOCRATIC REPUBLIC (G.D.R.) AND AUSTRIA

The most advanced plasma technology development in the G.D.R. and in Austria has been the DC plasma melting furnaces of VEB Edelstahlwerke in Freital.

2.3.7 Freital DC Plasma Melting Furnace

This furnace (see Figure 2-21) has three or four inclined plasma torches (cathodes) installed in the sidewalls and a single anode

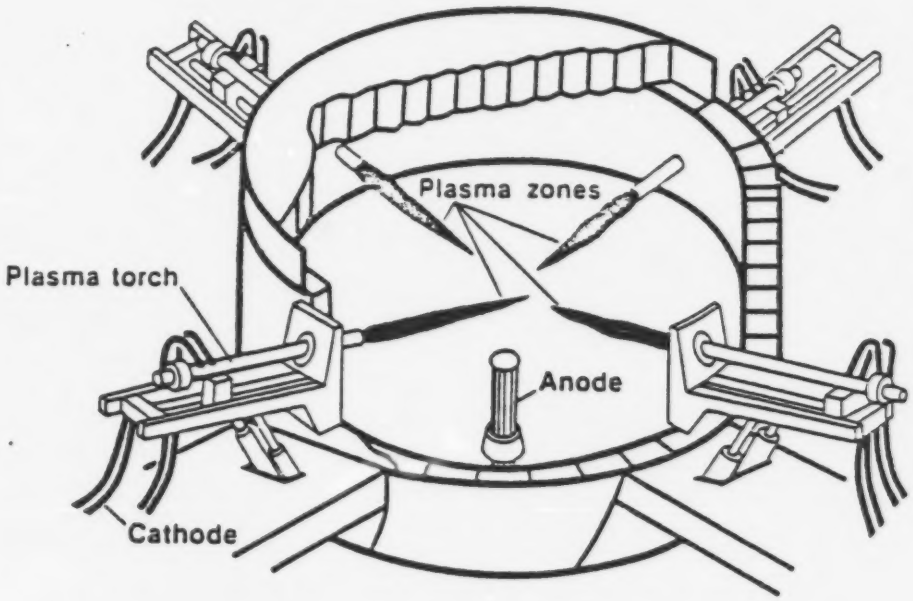


Figure 2-21 Freital DC Plasma Melting Furnace

in the bottom. The basic technology for these furnaces derived from U.S.S.R. research and commercial installations. A 10-tonne, 10-MW furnace has been in regular three-shift operation for over 10 years. A 30- to 40-tonne, 20-MW furnace was commissioned at Freital in 1977. The technical characteristics of 15-tonne (P 15) and 40-tonne (P 40) plasma furnaces at Freital are presented in Table 2-4 [36].

The Industrieanlagenbau Division of Voest-Alpine, Austria obtained the license for the Freital-type furnace in 1979. A 45- to 60-tonne furnace with four plasma torches, 36-MVA power rating is in operation at the Linz works of Voest-Alpine [35].

The maximum current for each torch is 10 kA. Torch positions during melting-down are adjusted so that the maximum energy emitted reaches the scrap in line with the arc. The actual

TABLE 2-4 Technical Characteristics of Freital DC Plasma Furnaces [36]

Parameter	Unit	Furnaces	
		P 15	P 40
Nominal capacity	tonne	15	40
Vessel diameter	mm	3,900	5,800
Max. DC capacity	MW	10	20
Max. DC voltage	volts	700	700
Power factor	Cos ϕ	0.9	0.9
Power supply voltage	kV	15	15
Power supply frequency	Hz	50 (60)	50 (60)
Argon consumption	Nm^3/h	15	60
Cooling-water consumption	m^3/h	100	160
Melting-down capacity	t/h	8-12	20-25
Melting-down energy consumption	kWh/t	450-550	450-500
Electrode life	hours	100	100
Mean refractory life	charges	150	150
Refractory consumption	kg/t	16/7	16/7
Noise level	dB	80	80

melting-down times obtained were 70 and 90 minutes for scrap of 1.8 t/m^3 and 2 t/m^3 densities respectively. This plasma furnace is planned to replace two 25-tonne electric-arc furnaces. The shell diameter of the furnace is 5.8 metres. At a power factor of 0.9 and installed power of 36 MVA, the DC power rating is 32 MW. Four torches of 7 to 8 MW each have separate electric power supply. Computer simulation has shown that furnaces up to 70 and 100 tonnes can be operated with a four-torch system. With higher capacity, more than four torches will be required [36].

Voest-Alpine is also negotiating the supply of a 10.8-MW plasma furnace to Samancor, South Africa for ferro-manganese fines melting [37].

SWEDEN

Sweden has made a remarkable contribution to the development of plasma technology. The two main companies carrying out this work are SKF Steel Engineering AB, and ASEA.

The SKF plasma generators were already discussed (see Section 2-2 above). Some plasma processes being developed by SKF Steel using SKF plasma generators are discussed in Chapters 3 and 4.

2.3.8 ASEA DC Plasma Arc Furnaces

ASEA has been involved jointly with Krupp, F.R.G. in the development of a transferred-arc plasma furnace (so-called single-electrode DC arc furnace) using a centrally installed graphite electrode as a cathode and a hearth anode (see Figure 2-22).

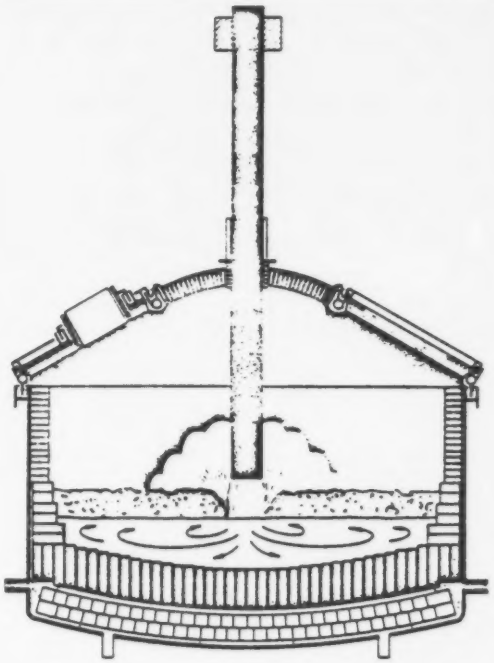


Figure 2-22 ASEA - Krupp Single (Graphite) Electrode DC Arc Furnace

A 50-tonne, 15-MW ASEA DC plasma-arc furnace is in operation for stainless-steel production at the Avesta Jernveks plant in Sweden since the second part of 1983 [37]. Also, a 20-MW ASEA DC plasma-arc furnace is installed at Krugersdorp division of Middelburg Steel & Alloys, South Africa for chromite smelting to ferrochrome.

ASEA has also made an effort to develop application of its DC plasma-arc furnace for the final reduction stage in the ELRED direct iron-ore smelting process which is competing with two other processes being developed in Sweden - INRED and PLASMASMELT (see details in Chapter 3).

FEDERAL REPUBLIC OF GERMANY (F.R.G.)

Plasma production of intermediate acetylene at Huels, F.R.G. has been in commercial operation since 1939. The Huels plasma reactor has already been discussed (see Section 2.2 above).

A 8.5-MW Huels plasma reactor designed for steam reforming of methane to reducing gas (carbon monoxide and hydrogen) to be used in the direct iron reduction unit (DRI) has been supplied by Huels to the Union Steel Company (USCO), South Africa.

The F.R.G. Ministry for Research and Technology has supported construction of a 15-tonne, 6-MW prototype DC plasma-arc furnace by M.A.N. - GHH Steerkrade and Brown Boveri. The furnace has been in operation in a steel foundry since mid-1982 [37].

2.3.9 Krupp Three-Phase AC Plasma Furnace

Krupp Research Institute (Forschunginstitut) in Essen, F.R.G. has been developing three-phase AC plasma furnaces for melting/remelting and ladle heating [38].

The development includes not only furnace design but also plasma generators and power supply system specifically for application in three-phase AC plasma furnaces.

A 3-tonne pilot furnace was constructed and commissioned in 1982. In this furnace, three AC plasma torches are mounted in the roof of the furnace. The torches are inclined towards the centre to keep the plasma arc at a reasonable distance from the furnace walls in order to minimize refractory wear. (See Figure 2-23).

The plasma torch consists of a water-cooled outer steel shroud with a replaceable nozzle and a central current-bearing rod with the tungsten electrode at the tip, the main electrode. A separate water-cooling circuit is used for cooling the main electrode.

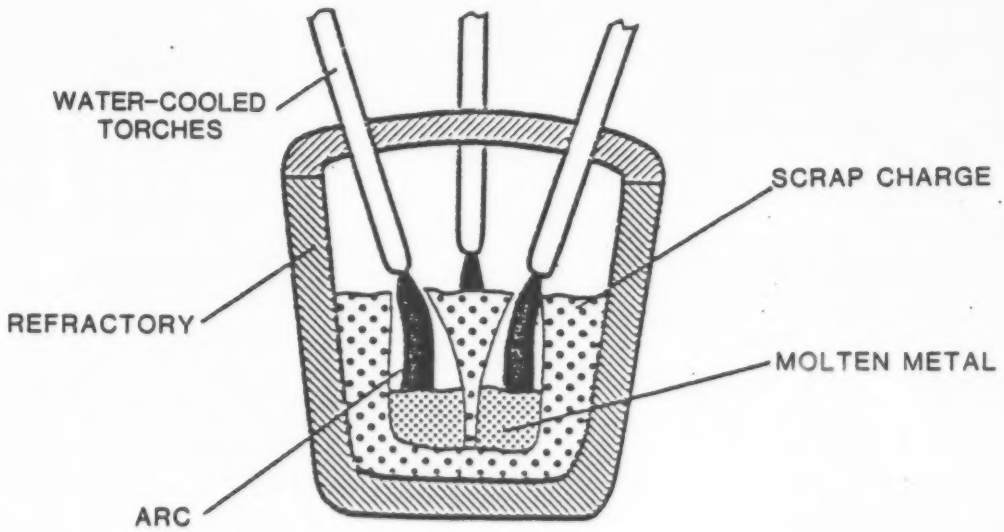


Figure 2-23 Krupp Three-Phase AC Plasma Arc Furnace

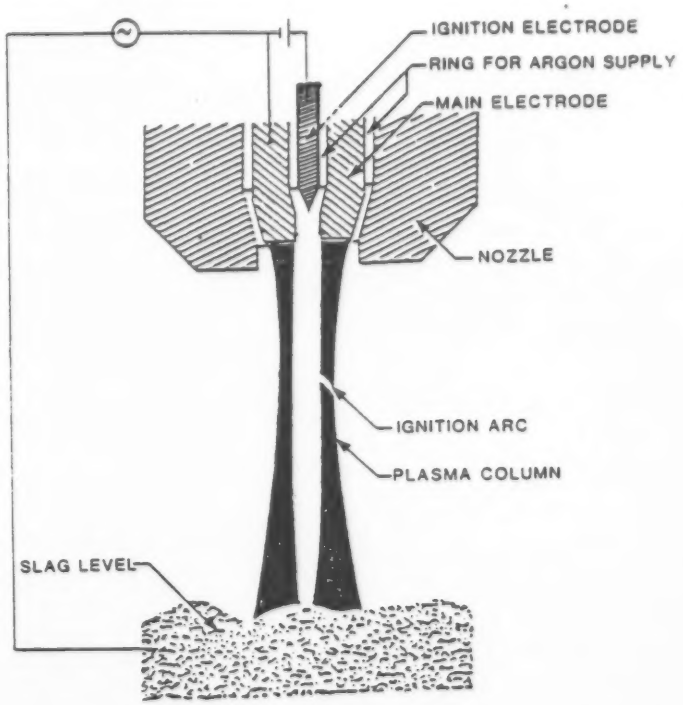


Figure 2-24 Principle of Krupp AC Plasma Torch

A starter electrode is located inside the main electrode (see Figure 2-24). For primary ignition, an DC arc is struck between these electrodes and argon is blown through the annulus producing a long slender starter flame. As soon as at least two of the furnace torches have established ionized paths to the scrap, the main AC arc is ignited between the torches and the starter arc is extinguished [38].

Tested plasma torch characteristics are presented below [38]:

Electric power rating	1.6 MW per torch (at 400 V)
Current	4.0 kA
Frequency	50 Hz
Arc length	up to 700 mm
Electrode life	100 h
Gas (argon) flowrate	7 m^3/h
Cooling-water flowrate	8 m^3/h
Torch diameter	108 mm
Torch working length	2000 mm

The melting tests carried out in the 3-tonne pilot furnace with scrap (packing density of 1.2 to 2.0 t/m^3), alloyed scrap and pig-iron have shown that the three-phase AC plasma arcs were quite stable after primary ignition. The primary ignition of these main AC arcs using a starter electrode was done without difficulty on cold scrap and melts at distances over 200 mm between the torches and the scrap/melt. No reigniting aids or permanent auxiliary arc was required.

During the melting tests, the AC arcs from the torches (kept always at a level slightly above the solid charge) first melt deep, relatively narrow craters into the scrap and quickly reach the furnace bottom forming a liquid pool, then the melt-down of scrap is started [11].

The results obtained in the 3-tonne pilot furnace during melt-down of steel scrap using 4-kA plasma torches and $7 m^3/h$ of argon flow rate for each torch are summarized below:

Melt-down time	56 minutes
Power consumption	650 kWh/t
Noise level	73 to 80 dB
Argon consumption	$4 m^3/t$

A 10-tonne, three-phase AC plasma furnace with 20 MVA power supply is being installed at Krupp Steel Works in Siegan, F.R.G. A 6-kA AC plasma torch to be tested in this 10-tonne furnace has been developed and planned to be ready for testing at the end of 1985. The 12-kA AC plasma torch is under development. The available 4-kA AC plasma torch may be sufficient for a 10-tonne melting furnace. With 6-kA AC torches, a 20-tonne furnace may be run. For a 50-tonne furnace, 12-kA AC torches are required according to calculations reported by Krupp [38].

UNITED KINGDOM

2.3.10 Tetronics Plasma Reactors

Tetronics Research and Development Company has developed the transferred-arc DC plasma furnace with mechanically precessing (about 50 r/m) torch (hot cathode) centrally mounted in the roof and anode in a form of water-cooled steel billet built into the furnace hearth (see Figure 2-25). The precessing of the torch, which is maintained at a small adjustable angle to the vertical axis of the furnace, facilitates even distribution of energy in the melt as well as aiding melt stirring [39].

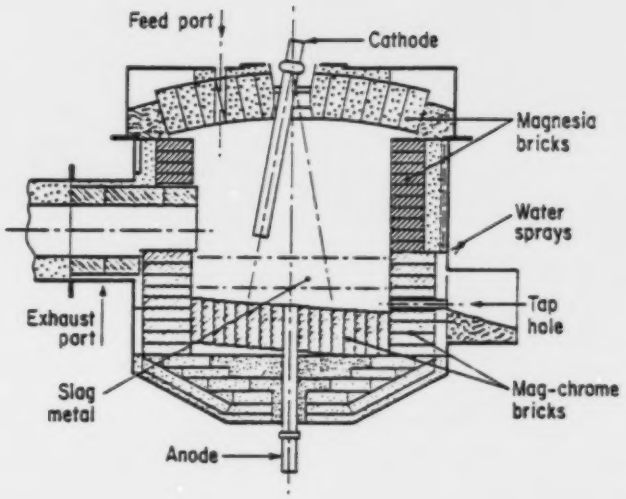


Figure 2-25 Tetronics Plasma Reactor

The plasma torch consists of a water-cooled copper tube with a thoriated tungsten tip concentrically located inside another water-cooled copper tube with a nozzle. A plasmagen gas (argon, helium or hydrogen) is passed through the annulus formed between the cathode tip and nozzle to cool the tip and stabilize the plasma-arc.

Primary ignition of the transferred plasma-arc generated between cathode and the molten bath or anode is carried out with a high frequency spark between the cathode tip and the nozzle followed by lowering the plasma torch or introducing a mobile auxiliary electrode into the furnace.

The Tetronics DC plasma furnaces of various sizes and torch ratings have been used for testing of several plasma applications

such as non-ferrous metals extraction (zinc and lead mostly) from steel mill dust [40], and melting and remelting of ferro-alloy fines. A new recent application consists of the recovery of platinum from General Motors discarded catalytic converters by Texas Gulf Minerals and Metals, in Alabama [34].

The 1.4-MVA Tetronics plasma furnace was used, in particular, in the development work of MINTEK, South Africa for smelting of chromite to high carbon ferrochromium (see "South Africa" below). Recently, results of the melting and refining of ferromanganese fines to produce slag-free bulk ferromanganese using the 3-MVA Tetronics pilot furnace were reported [39]. The feed materials were introduced continuously into the furnace through the feed ports located in the furnace roof and spaced at equal intervals around the central plasma torch. The gases evolved were removed through a single horizontal exhaust port.

The characteristics of the DC plasma torch used in these tests are presented below:

Diameter of torch	5 cm
Working length of torch	Variable, but typically 100 cm
Torch current	Typically 5000 A but up to 10,000 A tested.
Torch voltage	350 to 450 V depending upon feed material and arc length.
Arc length	10 to 100 cm
Torch rating	2.0 MW at 400 V
Gas consumption	7.5 m^3/h argon at 5000 A
Cooling-water flowrate	6.0 m^3/h
Cooling-water pressure	1 MPa
Energy loss to the cooling-water	60 kW
Electrode life	100 h

2.3.11 Davy McKee - PLASMACAN Reactor

As already discussed in Section 2.3.1 above, Davy McKee Research and Development Company has designed and built a 1-MW DC plasma reactor based on the patented Noranda configuration reactor. The furnace has been demonstrated by Davy McKee R & D on direct iron-ore smelting (see Chapter 3 for details), as well as on ferro-manganese melting.

2.3.12 Plasma Systems Multi-Torch Reactor (Furnace)

Plasma Systems Ltd., Croughton, Northants , U.K. has developed a novel DC plasma furnace system with three plasma torches located in the furnace roof around a central feed tube (see Figure 2-26). An electrically actuated starting electrode is also mounted on the furnace roof (not shown in Figure 2-26). The furnace may be operated in the non-transferred- and transferred-arc mode, using a conventional rammed lining or conducting crucible respectively [41].

The hot cathode and anode are water-cooled. A high pressure closed-loop cooling system for the cathode and a low pressure cooling system for the anode are used.

Three plasma torches arranged around a central feed tube generate a coalescent transferred-arc which allows a more uniform heating of the particulate material.

All three plasma torches operate from a common power supply. Operation of more than one torch from the same supply is made possible by stabilizing each torch individually. The high frequency ignition supply is used for starting the transferred-arc. The simplified scheme of multiple power supply is presented in Figure 2-27.

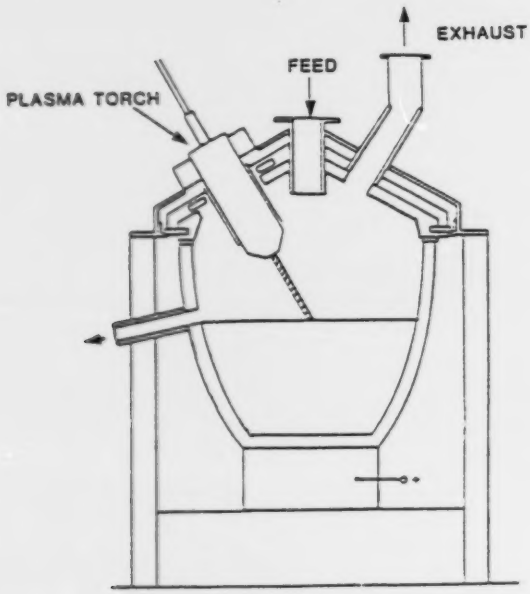


Figure 2-26 Plasma System Three-Torch Reactor

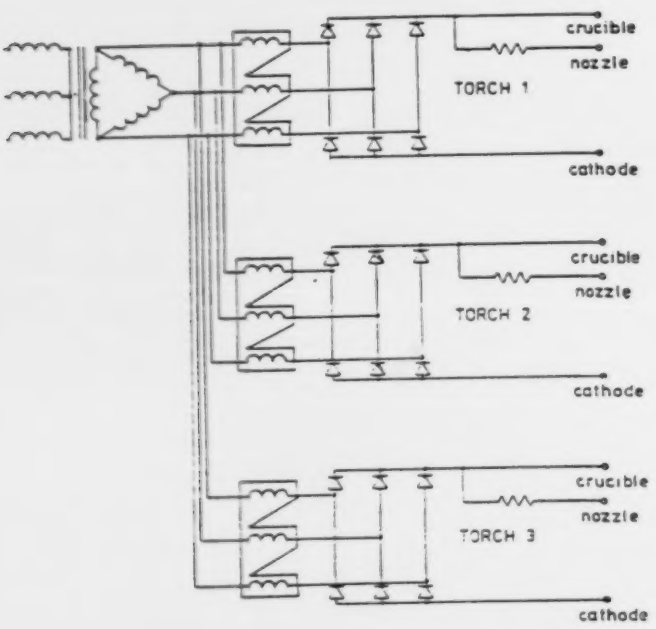


Figure 2-27 Multiple Output Power Supply for Three-Torch Plasma Systems Reactor (Furnace)

A pilot-plant furnace incorporating three DC plasma torches, rated at 0.1 MW to 0.35 MW of total output supplied from a single source have demonstrated that an arc length of 0.5 m at currents in the order of 200 A can be maintained at each torch. The furnace has been used for processing material at temperatures above 1200°C at feed rates up to 50 kg/h [41].

SOUTH AFRICA (S.A.)

Owing to large reserves of chromium and manganese ores, South Africa has a large installed capacity (1200 MVA) of conventional submerged-arc electric smelting furnaces for production of ferro-alloys. The South African Council for Mineral Technology (MINTEK) started examining the potential of thermal plasma application in the field of pyrometallurgy in 1976. Particular attention was paid to the use of plasma as the source of the high temperatures required for processing of ferro-alloys [42].

The intensive research and development work carried out by MINTEK in conjunction with Middelburg Steel & Alloys Company (MS & A) has already resulted in one of the world's largest commercial-scale plasma applications: a 20-MVA plasma furnace (supplied by ASEA) has been in operation at the Krugersdorp division of MS & A and has already produced several thousand tonnes of ferrochromium from chromite fines. (See Chapter 4 for details).

Two other industrial-scale plasma technology developments in South Africa are: plasma production of reducing gas for direct iron-ore reduction at Union Steel Corporation and ferro-manganese fines plasma melting at Samancor.

Union Steel Corporation (USCO) is in the process of installing five 8.5-MW Huels plasma reactors for plasma steam reforming of

hydrocarbon gas to reducing gas at USCO direct iron-ore reduction units (for more details see Chapter 3). Installation of 10.8-MW plasma furnace at Samancor for ferromanganese fines melting is being discussed with Voest-Alpine, Austria.

U.S.S.R.

For many years now, extensive research and development work on plasma technology and its industrial applications has been carried out in the U.S.S.R. Nevertheless, while numerous publications are available on research in thermal plasma chemistry, plasma diagnostics, etc., limited specific data on commercial plasma applications in the U.S.S.R. are available. Plasma furnaces up to 100 tonnes capacity have been reported to operate for ferro-alloy smelting and hot metal production using several plasma torches, 3.5 MW input power each [43]. Various types of plasma furnaces with hollow consumable electrodes have been used for production of nitrogen-alloyed steel, also plasma melting reactors with several plasma torches (so-called plasmatrons) mounted around the electrode to be melted are reportedly operating in the U.S.S.R. [37]. As has already been discussed (see Section 2.3.7 above), the VEB Edelstahlwerke/Voest Alpine (Freital) DC plasma furnace development is based on Soviet developments in the field.

From the limited specific information on commercial plasma capacity installed, it appears that the U.S.S.R. has a leading position in commercial plasma installations for primary melting and various remelting applications.

Applications of some plasma generators and reactors (furnaces) discussed in this chapter in several industrial sectors or processes are presented in the following chapters 3, 4, 5 and 6 with the emphasis on the potential for their application in Canada.

CHAPTER 3

PLASMA APPLICATION IN IRON AND STEEL PRODUCTION

3.0 PLASMA APPLICATION IN IRON AND STEEL PRODUCTION

Iron and steel are two of the most used materials worldwide. Production of steel in Canada reached 16 million tonnes in the year 1979.

Iron and steel production involves intensive energy-consuming processes carried out at high temperatures. Therefore, the development of plasma processes for this industry traditionally attracted the attention of engineers and scientists in the plasma field.

In ironmaking, the principal traditional process for producing large quantities of molten iron (hot metal) from iron ore is the blast furnace. For smaller scale applications, the direct reduction of iron ore to solid iron (DR process) is becoming increasingly common.

In steelmaking, the hot metal from blast furnaces is processed into steel in most cases by the basic oxygen process (BOP) in which molten iron and steel scrap are subjected to treatment with pure oxygen. The iron from DR units is processed, together with steel scrap, into steel in electric-arc furnaces.

In modern practice, the final stage of steelmaking often takes place in ladles. This stage may involve degassing, stirring, temperature adjustment, addition of alloying elements, etc., while keeping the temperature in the ladle above the melting point of steel.

The Canadian integrated steel producers, Stelco, Dofasco, Algoma, and Sysco accounting for about 85% of national steel production, use blast furnaces with coke (produced in coke ovens from metallurgical coal) as a major source of energy. Sidbec-Dosco, with about 8% of Canadian steel production, employs a DR (Midrex) process with further processing of sponge-iron produced, together with scrap, in electric-arc furnaces. Mini-mills, i.e., smaller local steel producers, make up the remaining Canadian steel production. Electric-arc furnaces in which scrap is used as feed (in some cases with DR sponge-iron to control impurities) are employed mostly in the mini-mills. Special steels, special products (pipes, etc.,) and cast products are included in Canadian iron and steel production [44].

Iron ore in Canada is mined in Ontario, Québec, Newfoundland and Labrador. Most of the ore mined in Ontario is consumed in the province. Also, substantial amount of iron-ore pellets are imported by Ontario steel producers from Québec, Labrador and the United States. Of the iron ore mined in Québec and Labrador, a substantial amount is exported. Approximately 9 million tonnes of this iron ore were exported and 3 million tonnes were used for Canadian needs, in 1983 [44].

The potential plasma applications in iron production, based on worldwide developments in the field, for both plasma-upgrading of conventional blast furnace and DR processes and new direct iron-ore smelting processes are discussed below. Also, the comparative economic considerations on the use of direct plasma iron-ore smelting in Canada versus conventional blast furnace and DR (Midrex) processes or new INRED (Intensive Reduction) and ELRED (Electric Reduction) processes, are presented.

3.1 PLASMA UPGRADING OF BLAST FURNACES

The conventional blast furnace iron-ore smelting process consists essentially (see Figure 3-1) of a blast furnace (vertical shaft, up to 30 m high and up to 15 m in diameter), together with hot-blast stoves and a gas cleaning system, preceded by a sintering or pelletizing plant and coke ovens.

Iron ore (as lumps, pellets or sintered with coke breeze) is charged together with coke and limestone (flux) at the top of the blast furnace, while the hot blast air or oxygen is blown through the tuyeres located at the lower part of the furnace.

The off-gas produced (containing H_2, CO, CO_2, H_2O, and N_2) is cleaned before use within the plant.

The molten-iron (hot metal) and slag are tapped out from the hearth at the bottom of the furnace.

The coke provides both heat and reducing gas for endothermic reduction of the iron ore and carburization of the iron. Usually, about 60% of the coke is spent to generate the gas, 30% is consumed for reduction and solution loss reaction, and the rest is adsorbed in the iron carburization [45].

Due to obsolescence of some coke ovens in Canadian integrated steel plants, coupled with increasingly stringent environmental protection standards, the plasma upgrading of existing blast furnaces to reduce coke consumption may be attractive, even if it will not result in substantial reduction of operating cost of the plants.

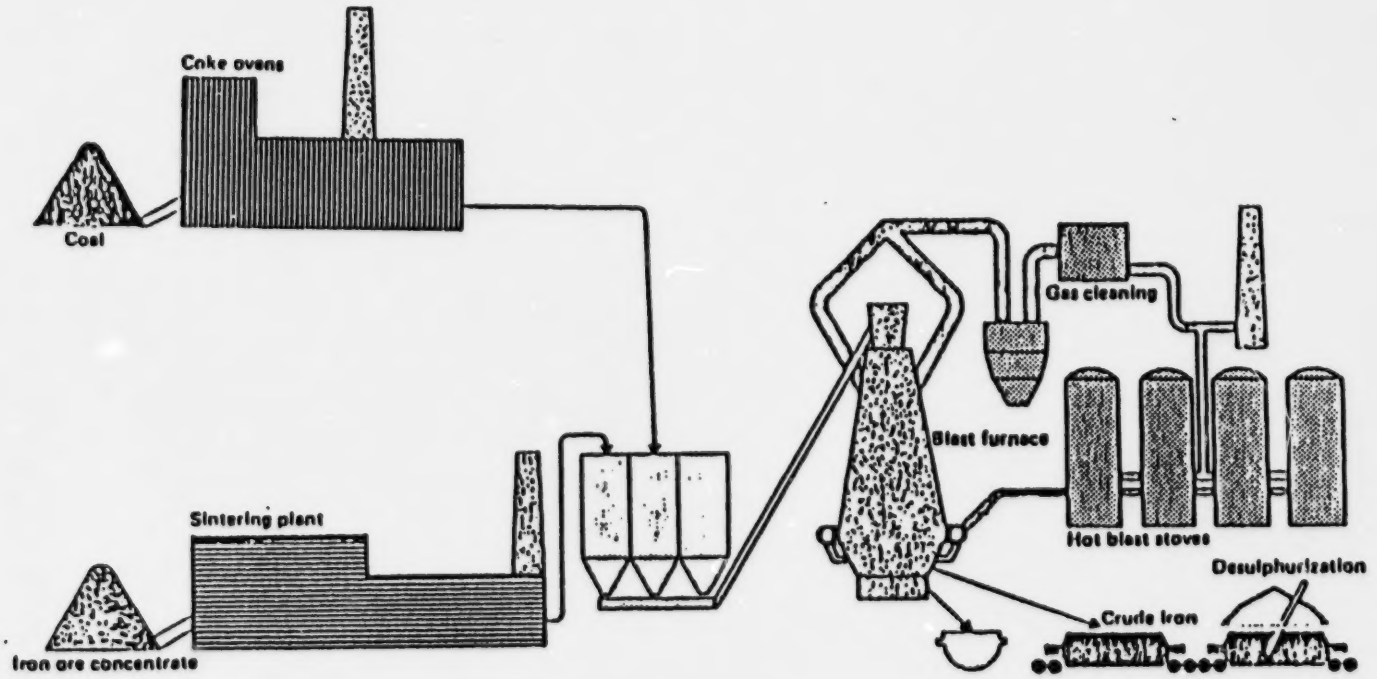


Figure 3-1 Simplified Flowsheet of Conventional Blast Furnace Iron-Ore Smelting Process

3.1.1 PIROGAS Process

A concept of plasma upgrading of a conventional blast furnace using plasma injection of reducing overheated gas (PIROGAS) process was proposed by the "Centre de Recherche Métallurgique (CRM)", Belgium [46].

It was possible to reduce the coke consumption of the CRM experimental blast furnace (Figure 3-2) from 717 kg/MTHM to 179 kg/MTHM (metric tons of hot metal produced) by substituting blast air heated to 750°C with plasma superheated reducing gas at a temperature above 2000°C. Up to 77% of the coke burnt out in the tuyeres and 91% of the coke for solution loss have been replaced by superheated reducing gas [47].

In modern blast furnaces, the coke consumption will be reduced by about 82% according to CRM calculations (see Table 3-1) [46].

Table 3-1 Coke Consumption Reduction in Blast Furnaces by Injection of Plasma Superheated Reducing Gas [46]

Amount of Coke Used	Blast Furnace kg/MTHM	PIROGAS kg/MTHM	Coke Savings kg/MTHM
Coke burnt at tuyeres	275	11	264
Coke for reduction	140	19	121
Coke for carburization	55	55	0
Total Coke	470	85	385

The reducing gas (superheated in a plasma torch to above 2000°C) is injected through the existing tuyeres of the blast furnace along with the hot blast-air from the stoves. Preliminary testing at CRM has shown that it is possible to produce superheated reducing gas by plasma reforming of natural gas with air or with CO_2.

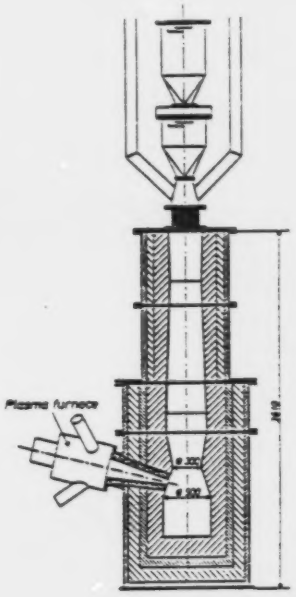


Figure 3-2 Experimental Blast Furnace at CRM

Table 3-2 shows a typical composition and temperature of reducing gas obtained in these experiments (note that argon was used as pilot gas, therefore the reducing gas was diluted with argon) [45].

Table 3-2 Composition and Temperature of Reducing Gas [45]

	Natural Gas/ Air	Natural Gas/ Carbon Dioxide
Temperature °C	2,020	2,180
Carbon Monoxide, CO %	18.1	41.2
Carbon Dioxide, CO_2 %	0.1	1.7
Methane, CH_4 %	0.1	0.5
Hydrogen, H_2 %	35.7	36.5
Water, H_2O %	1.3	2.8
Nitrogen plus Argon, N_2 + Ar %	bal.	bal.

The preliminary tests at CRM showed that about 137.2 kWh of electrical energy and 66.3 m^3 of natural gas can replace 100 kg of coke in the production of one tonne of hot metal [48]. Based on these preliminary data, no drastic reduction in production cost is anticipated at current costs of electricity, natural gas, and coke in either Québec, Ontario or Nova Scotia (See Appendix).

The PIROGAS process was further demonstrated in a small (500-t/d) blast furnace at Cockerill Steel plant in Seraing, Belgium, using a 3.5-MW Westinghouse plasma torch installed in one of the eight tuyeres of the furnace [46]. No data are available.

3.1.2 New Developments of Plasma Blast Furnace Upgrading

The development of plasma upgrading of a conventional blast furnace is also taking place in France. Aerospatiale jointly with Jeumont-Schneider and Électricité de France (EDF) has tested plasma blast-air heating using a Mobile Plasma Unit already described in the previous chapter. The 2.1-MW plasma torch of the unit was installed at the existing iron-ore blast furnace (production capacity 1300 t/d) at the Uckange, Lorraine plant, and tested during January 1985 [49]. Four 2-MW torches will be installed in the blast furnace (production capacity 1600 t/d) in the Uckange plant in 1986. Also, three Aerospatiale 1.5-MW DC plasma torches are in operation in the blast furnace at the Boulogne-sur-Mer ferro-manganese plant [14]. Institut de Recherche de Sidérurgie (IRSID) is participating in these tests. The results are not yet available. Installation of six additional 1.5-MW Aerospatiale plasma torches is projected at the Boulogne-sur-Mer plant in 1985-1986 [50].

One of the competing (or perhaps complementary, if used in conjunction with plasma torches) approaches aimed at reduction of coke consumption in conventional blast furnaces is the injection of pulverized coal with air or oxygen through the tuyeres. This concept is currently under investigation by a number of companies worldwide including IRSID in France and Stelco in Canada. As reported by IRSID, injection of low volatile coal at the rate of 113 kg/t of iron produced in No. 2 blast furnace at USINOR's Dunkirk plant resulted in the reduction of dry coke consumption from 446 to 360 kg/t of iron [51].

3.2 PLASMA UPGRADING OF DIRECT IRON-ORE REDUCTION PROCESSES

Blast furnaces are efficient and economically viable when producing large quantities of hot metal; a modern blast furnace produces in excess of 10 000 t/d of molten iron.

Not all steel plants, however, have need of such large quantities of iron and, furthermore, many of these steel plants are in developing countries and lack metallurgical coal but have an abundance of natural gas. Thus, in recent years, a number of smaller scale direct iron-ore reduction processes have been introduced and operated worldwide.

In the most widely used DR processes, iron ore, usually in the form of pellets (occasionally as lump ore), is treated with reducing gas and transformed directly into solid iron at a temperature below the melting point of any materials involved. Because of the porous structure of iron produced, the DR product is called sponge-iron. Plasma technology has been considered for preparation of reducing gas in two of the DR processes: Wiberg and Midrex.

3.2.1 Wiberg DR Process

In the conventional Wiberg DR process (see Figure 3-3), the reducing gas (about 20% to 30% H_2 and 70% to 80% CO) is produced at a temperature of about 1035°C in an electrically heated coke or charcoal carburetor. The gas passes through a bed of limestone or dolomite, to remove sulphur before entering the reduction zone of the shaft where iron-ore reduction takes place.

Plasma upgrading of the Wiberg DR process has been developed and demonstrated by SKF Steel Engineering in their Hofors plant in Sweden. The final version of this plasma process is known under the trade name PLASMARED [16].

The old Wiberg DR plant, with a capacity of 25 000 t/yr sponge-iron, was in operation in Sweden from 1955 until it was shut down in 1978 because of escalating production costs. In 1981 the coke carburetor of the Wiberg process was replaced by an LPG gasifier equipped with three 2.5-MW, single-gap Westinghouse plasma torches. LPG was used as fuel to generate the reducing gas. Because water was used as oxidizing medium, the electricity consumption of the modified process was comparatively high (about 1450 kWh/t of sponge-iron produced).

In 1982, a new gasifier was installed for operation with coal/water slurry and other fuels. Also the Westinghouse plasma torches were replaced by three 3-MW SKF Steel segmented plasma generators (See Figure 3-4).

The new entrained-bed gasifier is a cylindrical vessel lined with a refractory (70% alumina and 30%, silica). The gasifier is operated at a sufficiently high temperature to fuse and keep the slag in a molten state. The molten slag is discharged through

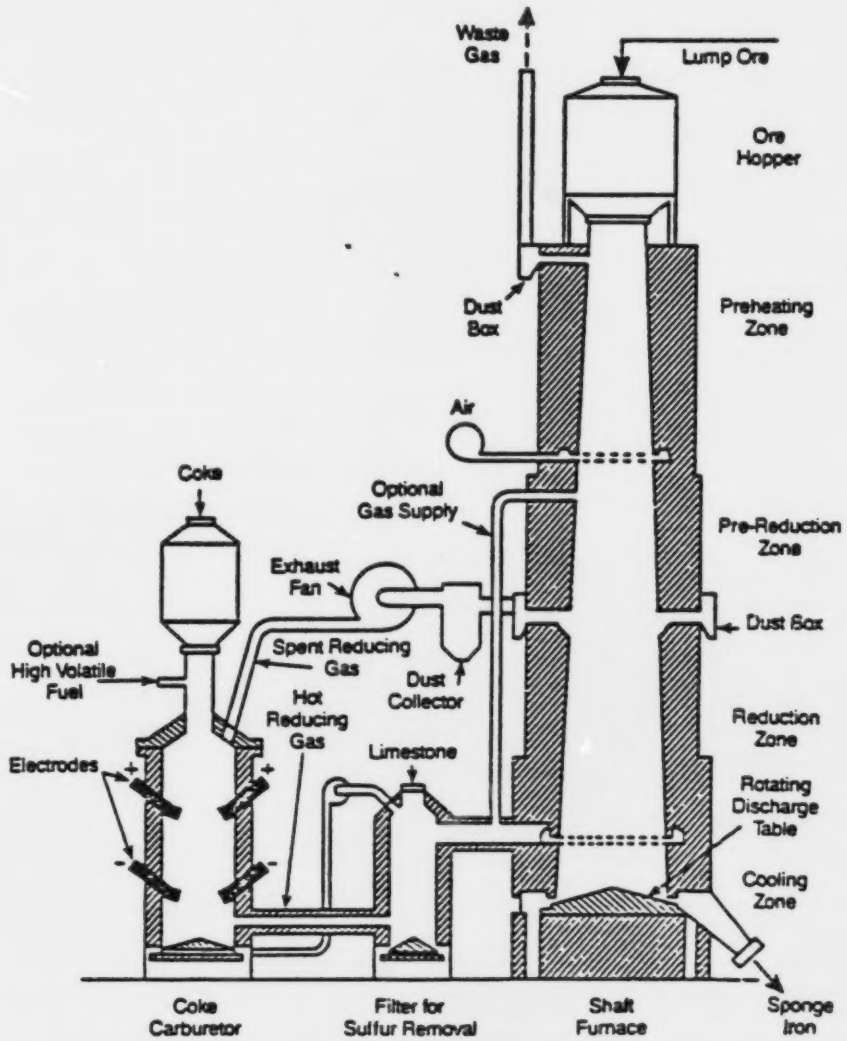


Figure 3-3 Simplified Flowsheet of Conventional Wiberg DR Process

a nozzle located at the lower part of the gasifier. The reducing gas leaves the gasifier at a temperature of 1000° to 1400°C (depending on the type of fuel used) and is injected into the reduction zone of the DR shaft. In May 1983, the three 3-MW plasma generators were replaced by a single 6-MW SKF Steel, generator mounted at the upper part of the gasifier (see Figure 3-4). In this case, however, the temperature in the lower part of the gasifier was not high enough to keep the slag in the molten state, which resulted in blockage of the plasma discharge nozzle. The plant, therefore, has been operated since June 1983 with oil as a fuel [16].

3.2.2 Midrex DR Process

The Midrex process is the most widely used DR process. This process has been used by Sidbec-Dosco at their Contrecoeur plant in Québec since 1973. In this process (see Figure 3-5), natural gas is used to generate reducing gas by catalytic reforming. The Midrex process has three main components: DR shaft furnace, catalytic reformer, and process-gas purification system.

The DR furnace is a steel vessel with an internal refractory lining in the reducing zone. The iron-ore pellets introduced at the top of the furnace descend continuously by gravity through the preheating, reduction, and cooling zones. The cooled direct-reduced iron continuously discharged at the bottom of the furnace is screened for removal of fines [52]. Reducing process gas, about 95% of combined CO and H_2, enters the furnace below the reduction zone and flows upwards countercurrent to the descending solids. The reducing gas leaving the top of the DR furnace, having about 70% of combined CO and H_2, is cooled and scrubbed to remove the dust particles. The main portion of this gas is compressed, enriched with natural gas, preheated to 400°C, and recycled through the gas reformer.

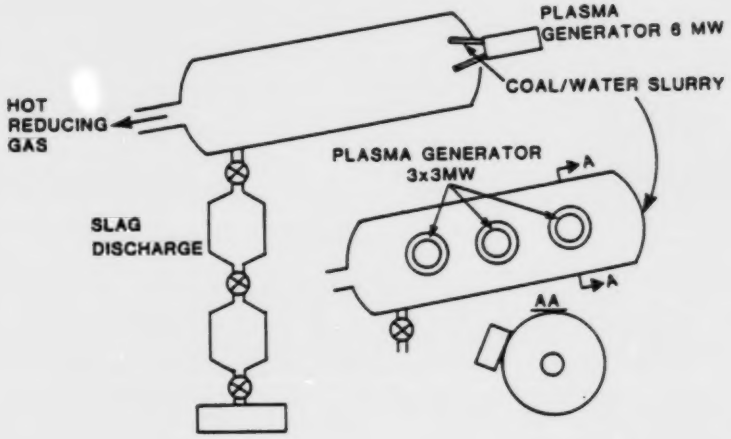


Figure 3-4 Modifications to SKF Plasma Gasifiers for Reducing Gas Preparation in Wiberg DR Process

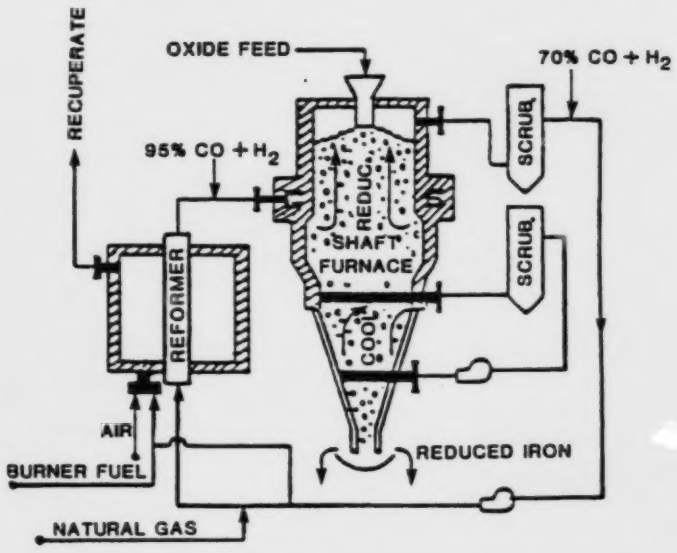


Figure 3-5 Simplified Flowsheet of Conventional Midrex DR Process

Plasma application in connection with the Midrex DR process has been considered by Sidbec-Dosco using plasma steam reforming of natural gas. Techno-economic assessment has shown, however, that, under present conditions, such plasma application is not economically viable even at the relatively low price of electricity in Québec [53]. Details are proprietary.

As mentioned earlier, plasma application in the DR process has been considered also in South Africa using steam reforming of hydrocarbon gas. The project, incorporating five 8.5-MW Huels plasma torches designed specifically for such an application, is in progress at the Union Steel Corp. (USCO) DR plant. As hydrocarbon feed gas to this plant, the by-product gas containing CO, CH_4, and H_2 from coal-synfuels SASOL plant will be used [54]. At the present time the first 8.5-MW plasma torch supplied by Chemische Werke Hüls, F.R.G., is on trial runs at USCO [55].

3.3 NEW PROCESSES FOR DIRECT IRON-ORE SMELTING

Plasma upgrading of blast furnaces cannot eliminate the need for iron-ore agglomeration or sintering plants, coke ovens or large production volumes, nor will it reduce the high capital investments involved. New processes should allow efficient direct smelting of finely divided particles of iron ore (i.e., without pelletizing or sintering) into liquid iron or steel, with drastic reduction (or even elimination) of coke consumption. At the same time, these processes would be on a smaller scale than that of blast furnaces; this could result in reductions of capital investment per tonne of iron produced and lower production cost. None of these new processes, however, has yet been demonstrated on a commercial scale.

A brief discussion on some of the direct iron-ore smelting processes is presented below.

3.3.1 Bethlehem Steel Plasma Direct Iron-Ore Smelting Process

In the Bethlehem Steel Plasma Direct Iron-Ore Smelting process, the finely divided iron-ore concentrates are reduced in one step to a virtually pure iron product with low carbon content. The falling-film plasma reactor used has already been described in Chapter 2. In this one-step direct iron-ore smelting process, electricity is used to provide both the endothermic heat of reaction and the latent and sensible heat requirements.

Experiments carried out at Homer Research Laboratory, Bethlehem Steel using 100-kW and 1-MW falling film reactors have demonstrated the possibility of reducing fine iron-ore concentrate into molten iron containing 0.005% S, 0.001% P, 0.006% C, 0.06% Si, and 0.007% Cu [56]. Low sulphur, low phosphorous Carol Lake hematite concentrate was used in these tests. The use of high-sulphur and high-phosphorous ores resulted in a corresponding increase in sulphur and phosphorous content in the product.

The lowest energy consumption reported with a 1-MW plasma reactor (without taking into account the energy lost to the heater cooling water) was 2650 kWh/MTHM. This value was obtained using hydrogen - natural gas mixture, (H_2/NG = 2) [56].

The material and energy balance analysis presented in Table 3-3 has been worked out by Amouroux et al. [57], based on Bethlehem Steel data.

Table 3-3 Bethlehem Steel Plasma Direct Iron-Ore Smelting Material and Energy Balances

Components	Input	Components	Output
Ferric Oxide	1.493 t	Iron	1 t
Methane	667 m^3/t	Carbon Monoxide	309 m^3/t
Hydrogen	333 m^3/t	Water	242 m^3/t
		Carbon Dioxide	24 m^3/t
		Hydrogen	1090 m^3/t
Electricity	3650 kWh/t	Recoverable Energy	755 kWh/t

It was concluded by Bethlehem Steel and others that the electricity requirements were too high for economic steelmaking using plasma [48]. Bethlehem Steel therefore, did not proceed with further scaling-up of this process for iron-ore smelting. Nevertheless, the process has been considered for production of ferrovanadium (see Chapter 4).

3.3.2 PLASMASMELT Process

This process has been developed by SKF Steel Engineering, Sweden, for direct plasma smelting of finely divided iron ore. The process, known under the trade name PLASMASMELT, was demonstrated in the SKF Hofors pilot plant.

In the PLASMASMELT process, (see Figure 3-6) iron-ore fines are first pre-reduced to about 50% in two fluidized-bed reactors in series. The pre-reduced iron ore is then injected into the lower part of the coke-filled, low-shaft furnace together with a slag former and reducing agent (powdered coal or heavy oil). The iron and slag are tapped from the bottom of the shaft. The process gas produced consists essentially of hydrogen and carbon

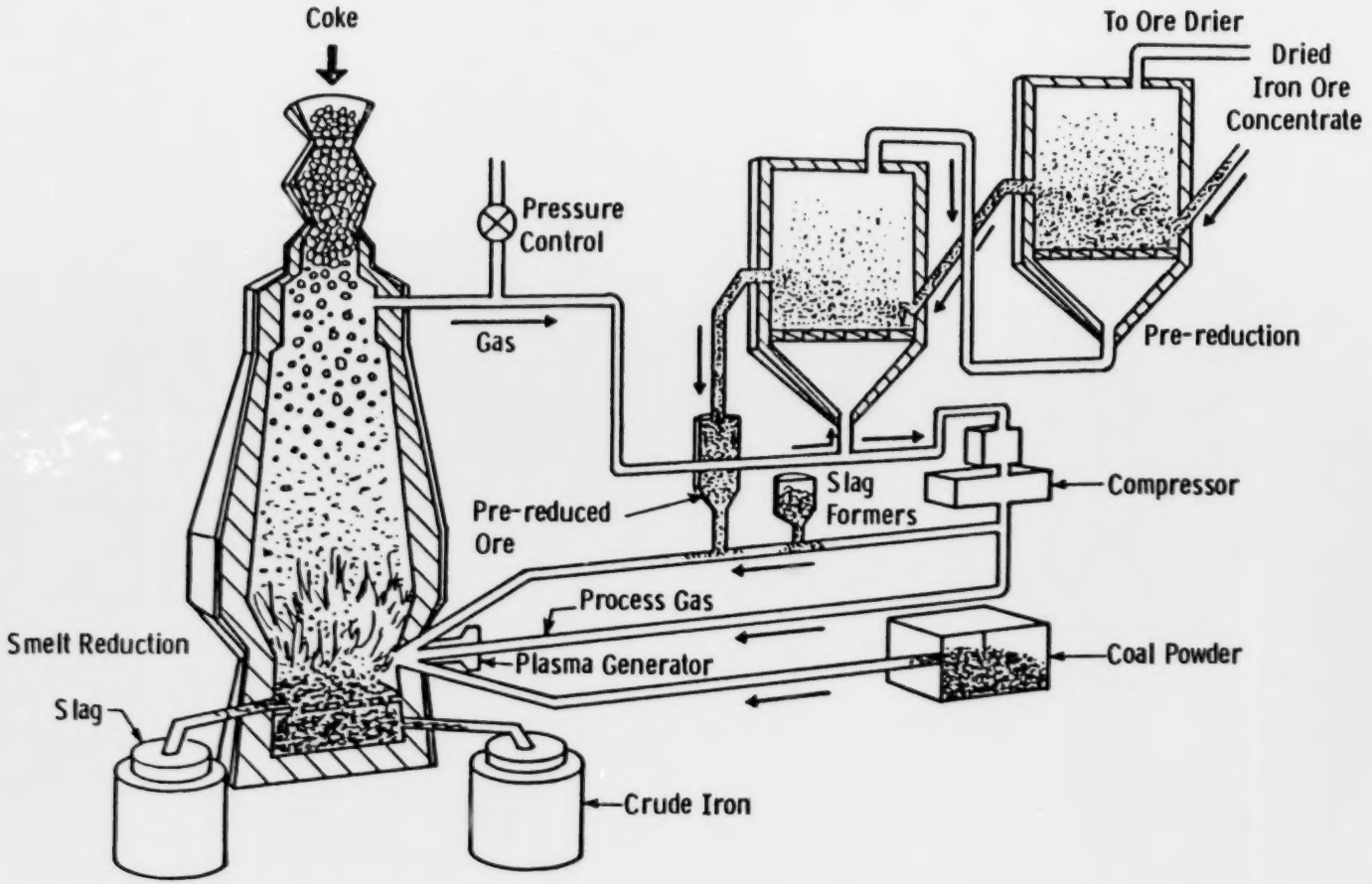


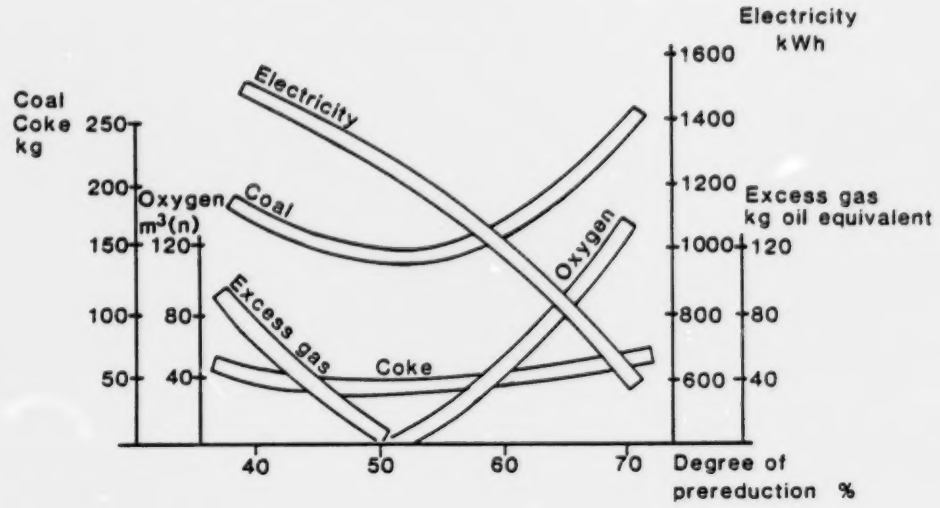
Figure 3-6 Simplified Flowsheet of SKF PLASMASMELT Process

monoxide. This gas, leaving the furnace at between 1000° and 1200°C, is cleaned and cooled to between 700° and 800°C before being admitted to the two-stage, fluidized-bed, iron-ore pre-reduction reactors. A portion of the purified and cooled gas is compressed and recycled as plasma gas and as a carrier of iron-ore fines [58].

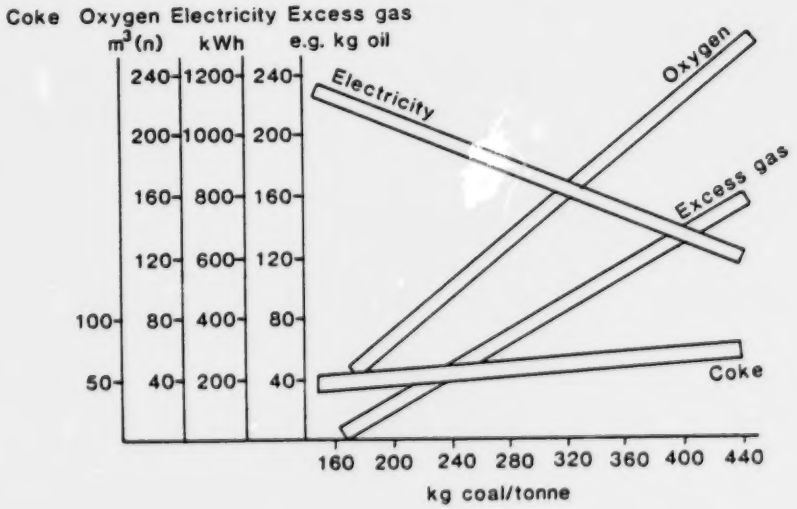
The exit gas from the fluidized-bed reactor, containing over 30% CO and H_2, is used for drying and pre-heating the ore. The liquid metal produced in the PLASMASMELT process is equivalent to blast furnace hot metal but has a lower sulphur content. The liquid metal, therefore, can be refined to liquid steel in a conventional basic oxygen process (BOP) operation, even without desulphurization (the sulphur content of the iron produced in the PLASMASMELT pilot-plant was as low as 0.01%) [48].

The PLASMASMELT furnace is designed as a refractory-lined shaft with tuyeres spaced symmetrically around the lower part of the furnace. Plasma generators and equipment for injection of solids and reducing agent are attached to the tuyeres. The function of the coke in the shaft is to form a reduction chamber which is permeable to gas and liquid and capable of withstanding high temperatures. Coke is also required to ensure reducing conditions along the refractory walls.

Because the required energy is provided by both electricity and coal in the PLASMASMELT process, the portion provided by electricity may vary depending on the local cost of electricity and coal (or other reductant to be used in the process). In Figure 3-7a, consumptions of electricity, coal, coke, etc., are presented as a function of degree of pre-reduction of iron-ore concentrate, in Figure 3-7b as a function of coal consumption [17].



a) Energy Balance as a Function of Iron-Ore Pre-Reduction



b) Energy Balance as a Function of Coal Consumption

Figure 3-7 PLASMASMELT Characteristics [17]

As shown in Figure 3-7, at 50% pre-reduction of iron ore, and about 150 kg/MTHM* of coal used, the electricity and coke consumptions amount to about 1250 kg/MTHM* and 50 kg/MTHM* respectively.

The PLASMASMELT process is not yet demonstrated as an integrated plant including ore pre-reduction utilizing recovery of enthalpy and reducing potential of the process off-gas.

3.3.3 Integrated Iron-Ore Pre-Reduction - DC Transferred-Arc Direct Plasma Smelting Process

The development and equipment design of the integrated iron-ore pre-reduction - DC transferred-arc direct plasma smelting process is being carried out by Davy McKee Research and Development at Stockton-on-Tees, England. The process includes the combination of the commercially proven Davy McKee FIOR (Fluidized-Bed Iron-Ore Reduction) system used for ore pre-reduction followed by the direct smelting of the pre-reduced iron ore in a DC transferred-arc plasma furnace of PLASMACAN configuration, discussed in Chapter 2 [5].

Ore pre-reduction was studied at Davy McKee using typical plasma furnace product gas and predictive modelling techniques. Power utilisation in iron-ore smelting reactions investigated in a 250-kg plasma furnace at three levels of input power and small variations of feed blend-rate is presented in Table 3-4 [5].

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* MTHM = Metric Ton of Hot Metal

Table 3-4 Power Utilization in Iron-Ore Smelting Reactions

Test No.	1	2	3
Input power kW	157	187	224
Total feed blend-rate kg/min	2.2	2.4	2.4
Basis of calculation, power input kW	100	100	100
Measured cooling water losses kW			
- cathode	0.3	0.6	0.9
- reaction sleeve	7.9	12.6	16.8
Furnace wall losses (calculated)	8.8	7.2	6.8
Total losses kW	17.0	20.4	24.5
Smelting requirements (calculated from products)			
- Sensible heat (1500°C) kW	41.8	40.6	36.4
- Reaction (25°C) kW	41.8	35.7	35.0
Total heat required kW	83.6	76.3	71.4
Total power demand kW	100.6	96.7	95.9
Power surplus %	-0.6	3.3	4.1
Percentage metallization, based on metal plus slag (carbon content of metal low in each case)	94.3	97.1	96.9

The information on electricity consumption per tonne of molten iron produced is not yet available. It may be anticipated, however, that in this integrated iron-ore pre-reduction and direct plasma-smelting system, the energy consumption would be substantially lower than that in the one-step Bethlehem Steel direct iron-ore plasma smelting process.

3.3.4 MESABI Metal Project

Among the recent research and developments in plasma direct iron-ore smelting, the plasma MESABI Metal project should be mentioned. This project was conceived in early 1983 by Pickands Mather & Co. (project manager), Westinghouse Electric Corp., and Minnesota Power, with funding from the Electric Power Research Institute U.S.A. [59].

The project consists of four phases: Phase 1: design, construction, and operation of a pilot plant, 0.5 t/h hot metal nominal capacity; Phases 2, 3 and 4: design, construction, and operation of semi-commercial demonstration plant, producing 100,000 t/yr hot metal. The last three phases will be based on the results obtained in Phase 1.

Westinghouse brings their plasma systems to this project. The objectives of the program are to define the process feasibility, using various Minnesota iron-ore concentrates, coal, and peat to produce iron or alloys utilizing plasma technology. At present, the work on Phase 1 is in progress.

ELRED and INRED are two direct iron-ore smelting processes being developed in Sweden. Neither has yet been demonstrated on a commercial scale.

3.3.5 ELRED Process

The ELRED (Electric Reduction) process has been developed jointly by the Swedish companies Stora Kopparberg Bergslags AB, and ASEA.

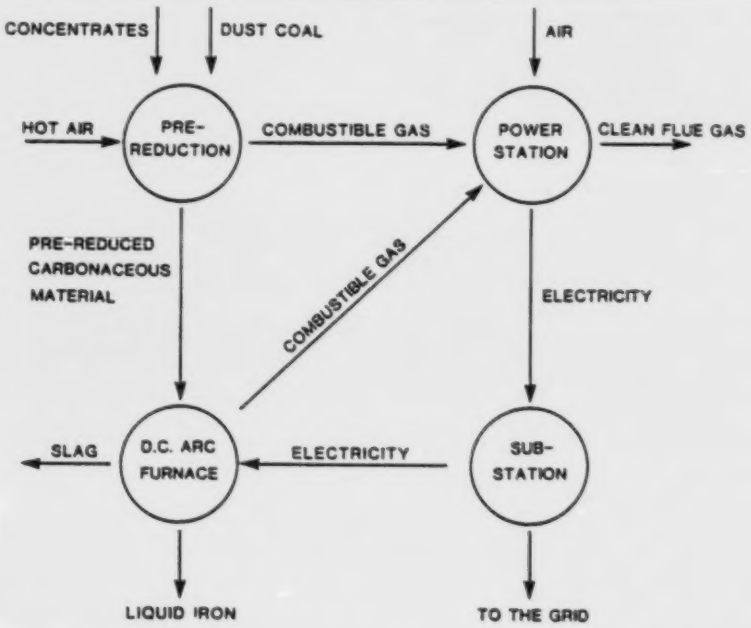

Figure 3-8 Simplified Block Diagram of ELRED Process

The ELRED process involved three main operations (as shown in Figure 3-8) [58]:

- ore pre-reduction to 60%-70% in circulating fluidized-bed;
- final reduction and smelting in electric-arc furnace;
- electric power generation from the off-gases.

The pre-reduction stage (see Figure 3-9), takes place at pressures up to 0.6 Mpa and at a temperature between 950° and 1000°C. The feed to this stage is a finely ground iron-ore concentrate (particle size less than 0.1 mm) with pulverized coal (steam coal, particle size: 0.2 to 0.3 mm). The dried iron-ore concentrate is heated to about 700°C by contact with off-gas from the fluidized-bed reactor. The material then passes through cyclones to the fluidized-bed reactor. Air and dried pulverized coal are injected into the main section of the fluidized-bed. The coal and air generate the required heat to maintain the bed temperature and also generate the gas mixture of carbon monoxide

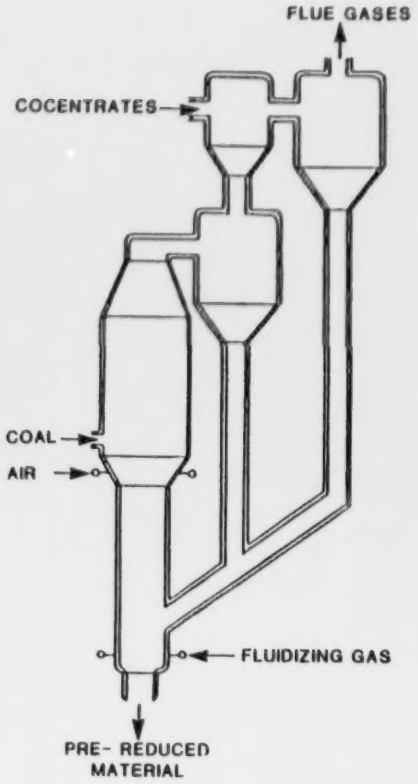

Figure 3-9 Pre-Reduction Stage - ELRED Process

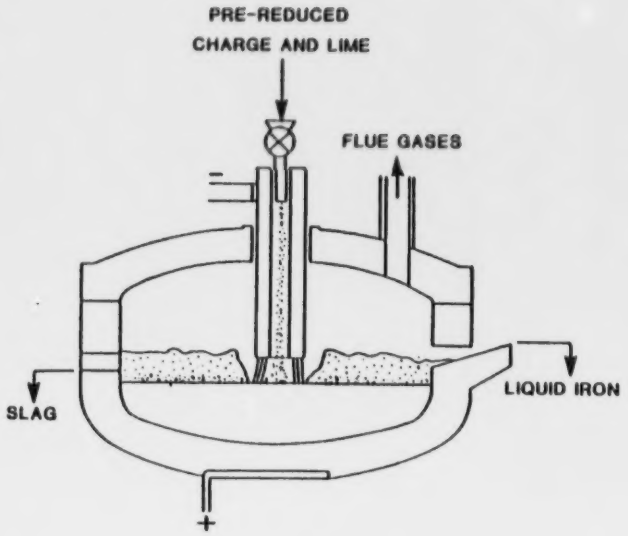

Figure 3-10 Final Reduction Stage - ELRED Process

and hydrogen necessary for reduction. About one-third of the fluidized-bed reactor off-gas is purified and recycled to the fluidized-bed reactor. The bulk of the off-gas is used as utility (preheating and generation of steam and electricity).

The pre-reduced material, having about 65% metallization (about 75% reduced), is continously discharged from the bottom of the reactor and directly transferred to the DC arc furnace, (shown in Figure 3-10), for final reduction. A hollow carbon electrode is located in the centre of the furnace roof and is connected to the negative pole of the rectifier. The positive pole is connected to a bottom electrode, which is in direct contact with the iron-ore smelt.

The pre-reduced material, which contains sufficent char to complete the smelting and carbonizing of the hot metal, is mixed with suitable fluxes and charged into the DC arc furnace at about 600° to 700°C. The material is fed through the graphite electrode. The hot metal produced contains 3.5% C, 0.05% Si, 0.05% Mn, and 0.30% S when using coal containing 1.0% S [60].

Hot metal production in the ELRED process would require about 700 kg of steam coal with calorific value of 6500 kcal/kg, or 4.5 Gcal (5.3 MWh) per tonne of iron. At the same time, surplus electric power of about 300 kWh/t of iron is generated and transferred to the power utility network. The net energy consumption is thus 4.2 Gcal/t (4.9 MWh/t) of hot metal [58].

3.3.6 INRED Process

The INRED (Intensive Reduction) process shown in Figures 3-11 and 3-12, was developed by Boliden AB, Sweden. The INRED process reduces iron-ore concentrates to molten iron in two stages in a single reactor and the hot gas produced is used to generate electricity. This process can also be divided in three main operations:

- flash-smelting/pre-reduction (first stage);
- electrical smelting/final reduction (second stage); and
- steam and electric power generation and oxygen production (third stage).

The first stage includes flash smelting and pre-reduction of iron ore concentrates with coal and oxygen in a water-cooled combustion chamber. The coal is partly burned and the remainder is transformed into coke. The ore is pre-reduced and the charge is superheated.

The charge (ore, coal, and limestone) is blown with oxygen into the flash-smelting chamber through a circular array of nozzles on the top of the chamber.

In the second stage, the pre-reduced and superheated material is collected with the coke from the first stage in the lower part of the reactor, which is an electric-arc furnace located below the combustion chamber. The smelted iron produced in the electric arc is considered equivalent to normal blast-furnace iron and, therefore, can be refined to liquid steel in a conventional BOP operation.

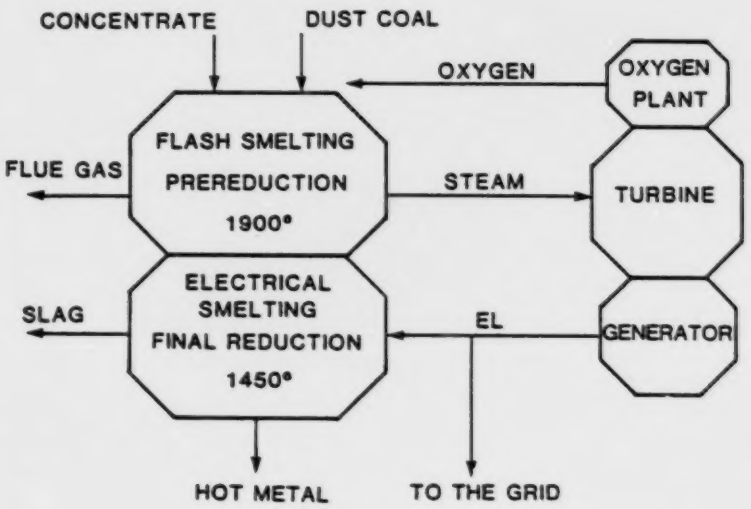

Figure 3-11 Simplified Block Diagram of INRED Process

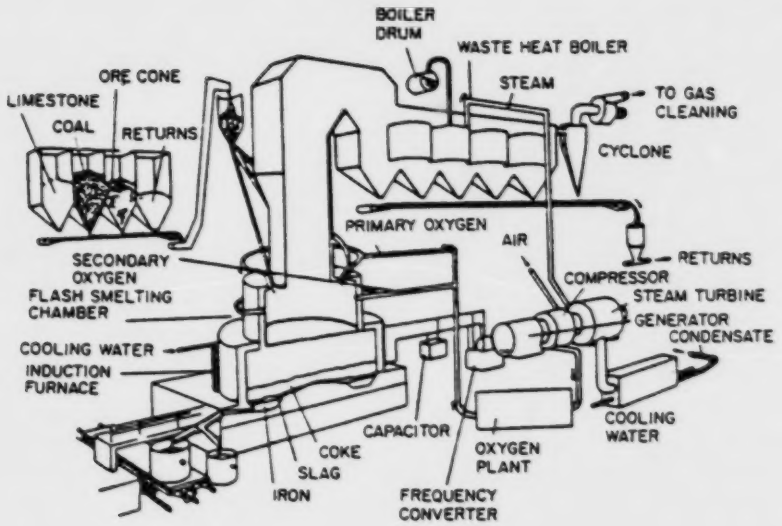

Figure 3-12 Schematic of INRED Process

The gases leaving the flash smelting chamber at a high temperature are cooled in a vertical gas take-off and in the radiating section of a steam generator to a temperature at which the dust in the gas will not stick at the entry to the convection section of the boiler. The steam produced is used to drive a turbine which powers the oxygen plant compressors and to generate electricity. The electricity generated is partly consumed by the electric furnace and surplus is transferred to the grid.

The energy consumption of the INRED process is estimated at 720 kg of coal (containing 6% moisture and 20% ash) which is equivalent to approximately 4.7 Gcal per tonne of hot metal. The final reduction furnace needs only some 300 kWh/t of iron. The thermal efficiency of the process is estimated at 65% to 70% [58].

3.4 COST CONSIDERATIONS

None of the above discussed direct iron-ore smelting plasma processes are yet in commercial operation. Therefore, it is not possible at the present time to make a cost estimation based on actual capital, operating, maintenance and other cost data.

A techno-economic feasibility study was carried out recently comparing a PLASMASMELT plant of 250 000-t/yr capacity (the smallest economically viable plant size considered by SKF Steel) with the smallest economically viable blast furnace having a capacity of 2 million t/yr of hot metal. According to this study, the estimated capital cost per tonne of molten iron produced per annum was substantially reduced in the direct plasma-smelting case due to elimination of sintering/pelletizing plants and coke ovens. Also, the calculated production cost of molten iron was reduced by about 20% [48].

A comparative cost estimate of liquid steel production from iron ore using conventional iron producing technologies (i.e., blast furnaces or various DR processes) versus several new direct iron-ore smelting technologies (including plasma) followed by BOP or electric furnace for iron conversion to liquid steel has been carried out by the US Steel Corporation in 1980 [60]. The same production rate of 6.8 million annual net metric tons of liquid steel (ANMTLS) was considered for each of the alternative processes.

A preliminary cost comparison of five alternative iron-steel-making processes discussed in Sections 3.1 and 3.2 of this Chapter (i.e., Blast Furnace - BOP, Midrex - Electric Furnace, PLASMASMELT - BOP, INRED - BOP and ELRED - BOP) is presented below for Canadian conditions taking the US Steel report [60] as the basis.

Material and energy consumptions as well as labour required per net metric ton of liquid steel for each of the processes considered are presented in Table 3-5. The costs of these items per ANMTLS produced (which comprises the variable cost of a product) are summarized in Table 3-6 (Sheet 1).

The preliminary estimate of the total annual production costs for a plant capacity of 6.8 million ANMTLS as well as the production costs in $/ANMTLS are summarized in Table 3-6 (Sheet 2). Also, the investment per ANMTLS is presented in this table.

The costs of materials and energy per MTLS have been calculated based on unit prices of these items in Canada (see Appendix). The unit prices obtained in US dollars have been converted to Canadian currency using an exchange rate of 1.36 (Royal Bank of Canada, Foreign Exchange, First Quarter 1985). It should be

noted that material unit prices may vary, in particular depending on special agreements between suppliers and users. Therefore, the unit prices in Table A-2 (Appendix), should be considered as average unit prices to be used for process comparison only. The components comprising annual production cost (other than variables cost presented in Table 3-6, Sheet 1) were calculated taking into account the basic financial assumptions and economic criteria accepted in this report and summarized in the Appendix. The investments per AMTLS are based on those presented in [60] and converted to March 1985 Canadian dollars.

Examination of the above data shows that among the alternative steelmaking processes considered, the lowest production cost may be expected for the PLASMASMELT - BOP process. The annual investment cost per tonne of liquid steel is the lowest for the Midrex DR - Electric Furnace process. The production cost, however, in this case is still higher than that for the PLASMASMELT - BOP process.

The lower production cost of the PLASMASMELT - BOP process in comparison to the base case (coke ovens - blast furnace - BOP) reflects partial substitution of coke and coal by higher consumption of electricity for direct plasma iron-ore smelting (1180 kWh/NMTLS versus 50 kWh/NMTLS) at the relatively low cost of electricity in Canada as well as lower investment/AMTLS required. The latter is due mostly to elimination of coke ovens and ore pelletizing plant associated with conventional blast furnaces.

Table 3-5 Summary of Alternative Steelmaking Processes, Material and Energy Consumptions per NMTLS

[Basis: 6.8 million Annual Net Metric Tons Liquid Steel (ANMTLS)]

	Units	Blast Furnace -BOP (Base Case)	Midrex DR-Electric Furnace	PLASMA-SMELT -BOP	INRED-BOP	ELRED-BOP
Ferrous Material						
Oxide pellets	NMT*Fe	0.722	0.8066			
Ore concentrates	NMT			1.328	1.4525	1.63
Alloys	NMT	0.010	0.01	0.01	0.01	0.01
Revert scrap	NMT	0.273	0.273	0.273	0.273	0.145
Scrap	NMT					
Dust and sludge (credit)	NMT	0.027	0.027	0.027	0.027	0.027
Fuel						
Coke	NMT			0.0415		
Coking coal	NMT	0.585				
Carbon additive	kg		6.00			
Low-S non-metal. coal	MT			0.1743	0.8549	0.653
Fuel	GJ		9.885	0.444	2.988	2.163
Fuel (credit)	GJ	4.07			10.62	
Electricity	kWh	50	20	1180	50	50
Electricity (credit)	kWh					307
Other Materials						
CaC_2	kg					8.35
Oxygen	m^3	56.19	4.6826	56.19	56.19	44.453
Electrode (graphite)	kg		6.00			
Electrode (self-baking)	kg				7.50	7.00
Limestone	NMT	0.21			0.19	0.235
Flux	NMT			0.058		
Lime	NMT	0.08	0.125	0.080	0.08	0.01
Spar	kg	4.00	4.00	4.00	4.00	0.50
Labour	Manhour	0.33	0.39	0.33	0.69	0.49

Source: C.G. Davis, J.F. McFarlin, and H.R. Pratt. Compilation of Reports on Direct Reduction Technology and Economics, IDO - 10095., U.S. DOE., June 1981.

* Net Metric ton

Table 3-6 Preliminary Cost Comparison of Alternative Steelmaking Processes
(Sheet 1 of 2)

[Basis: 6.8 Million Annual Net Metric Tons Liquid Steel (ANMTLS)]

Variable Costs/NMTLS, Canadian Dollars, March 1985

	Coke Oven-Blast Furnace-BOP (Base Case)	Midrex DR-Electric Furnace	SKF PLASMA-SMELT -BOP	INRED-BOP	ELRED-BOP
Ferrous Material					
Oxide pellets	57.90	60.50			
Ore concentrates			37.18	40.67	45.64
Alloys	6.00	6.00	6.00	6.00	6.00
Revert scrap	30.03	30.03	30.03	30.03	15.95
Dust and sludge (credit)	(1.86)	(1.86)	(1.86)	(1.86)	(1.86)
Total fer. mat. cost	92.07	94.67	71.35	74.84	65.73
Fuel					
Coke			5.73		
Coking coal	48.56				
Carbon additive		1.62			
Low-S non-metal. coal			12.55	61.55	47.02
Fuel		37.39	1.68	11.31	8.18
Fuel (credit)	(15.40)			(40.17)	
Electricity	1.19	19.68	28.33	1.19	1.19
Electricity (credit)					(7.38)
Total fuel cost	34.35	58.69	48.29	33.88	49.01
Other Costs					
CaC_2					3.76
Oxygen	3.93	0.33	3.93	3.93	3.11
Electrode (graphite)		18.00			
Electrode (self-baking)				3.38	3.15
Electrode Tungsten			1.40		
Limestone	2.73			2.47	3.06
Lime	6.56	10.25	6.56	6.56	0.82
Flux			4.35		
Spar	0.72	0.72	0.72	0.72	0.09
Refractory					1.50
Passivating		2.83			
Labour	6.24	7.37	6.24	13.04	9.23
Total other costs	20.18	39.50	21.50	30.10	24.72
Total variable costs	146.60	192.86	142.84	138.82	139.46

Table 3-6 Preliminary Cost Comparison of Alternative Steelmaking Processes
(Sheet 2 of 2)

[Basis = 6.8 million Annual Net Metric Tons Liquid Steel (ANMTLS)]

Annual Production Costs, millions of Canadian Dollars, March 1985					
	Coke Oven-Blast Furnace-BOP (Base Case)	Midrex DR-Electric Furnace	SKF PLASMA-SMELT -BOP	INRED-BOP	ELRED-BOP
Annual Variable Costs	996.88	1 311.45	971.31	943.98	948.34
Maintenance	101.50	71.83	87.84	115.56	132.50
Supervision	10.18	12.03	7.40	21.28	15.11
Supplies	14.85	17.54	10.81	31.04	20.00
Depreciation	169.17	119.72	146.40	192.59	220.50
Taxes & Insurance	76.13	53.87	65.88	86.67	99.20
Overheads	50.37	42.68	41.55	71.48	68.28
Total Annual Production Cost	1 419.08	1 629.12	1 331.19	1 462.60	1 503.93
Production Costs and Investment, Canadian Dollars, March 1985					
Production Costs Can $/ANMTLS	208.69	239.57	195.73	215.09	221.16
Investment Can $/AMTLS	497.56	352.12	430.58	566.45	648.74

The estimated investment ($/AMTLS) and production cost ($/ANMTLS) for INRED - BOP and ELRED - BOP are higher compared to both the base case and PLASMASMELT - BOP processes. The INRED - BOP and ELRED - BOP production costs are, however, lower as compared to that of Midrex DR-Electric Furnace processes.

It should be noted, however, that while the data estimated for conventional technologies are based on actual capital costs, material and energy consumption, etc., which have been proven in commercial operation, the data for new processes, (i.e., INRED, ELRED and PLASMASMELT) are based on pilot-plant demonstrations only, and further scale-up predictions and calculations to a commercial level of operation. The above cost estimates, therefore, should be considered as preliminary comparative cost considerations.

CHAPTER 4

APPLICATION OF PLASMA TECHNOLOGY

FOR PRODUCTION OF SPECIALTY (REFRACTORY)

METALS AND FERRO-ALLOYS

4.0 APPLICATION OF PLASMA TECHNOLOGY FOR PRODUCTION OF SPECIALTY (REFRACTORY) METALS AND FERRO-ALLOYS

Application of thermal plasma technology may be particularly advantageous for production of "specialty" metals* and their ferro-alloys, because these metals are characterized by high melting and boiling temperatures easily obtainable in thermal plasma systems. The specialty metals possess high strengths and generally good corrosion resistance; therefore, they are often called "refractory" metals.

The refractory metals and their ferro-alloys are also characterized by high selling price (except for ferrochrome) and substantial added value. This reflects in particular the high production costs for extracting and refining of the metals using existing technological processes [26].

Canada possesses substantial mineral resources containing various specialty (refractory) metals. In Québec, the estimated reserves of niobium are approximately 150 million tonnes with grade varying between 0.31% and 0.69% Nb_2O_5; estimated chromite reserves are 1.1 million tonnes at an average grade of 10.7% Cr_2O_3. The reserves of titanium are quite considerable (approximately 2 billion tonnes of ilmenite with about 37% Fe and 14% TiO_2 on average) [61]. The major Canadian molybdenite

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* This class of metals includes titanium (M.P. 1668°C, B.P. 3260°C); zirconium (M.P. 1852°C, B.P. 3580°C); vanadium (M.P. 1900°C, B.P. 3450°C); niobium (M.P. 2468°C, B.P. 3300°C); tantalum (M.P. 2996°C, B.P. 5425°C); chromium (M.P. 1875°C, B.P. 2665°C); molybdenum (M.P. 2610°C, B.P. 5560°C); and tungsten (M.P. 3410°C, B.P. 5930°C);

deposits are located in British Columbia (Lornex Mining Co., Ltd., about 416 million tonnes, grade 0.013% MoS_2; Boss Mountain, approximately 6 million tonnes, grade 0.14% MoS_2; Brenda, 100 million tonnes, grade 0.032% MoS_2; and others). Some molybdenite deposits are located in eastern Quebec and New Brunswick. Canadian resources of tungsten-containing ore are estimated at about 3 million tonnes, grade 1.32% WO_3, deposited mostly in the North West territories (NWT) and, to a lesser extent, in British Columbia [135]. In Manitoba, the resources of tantalite are about 1 million tonnes, grade 0.138% Ta_2O_5; the measured resources of chromite are approximately 15 million tonnes, of average grade, 4.55% Cr_2O_3, and 3.4 million tonnes, grade 13.43% Cr_2O_3 [136]. Considerable amounts of vanadium pentoxide are available in fly ash derived from oil sands in Alberta [62].

In 1981-1982, Canada produced large quantities of refractory metal concentrates (see Table 4-1). Most of these concentrates were exported [26].

Table 4-1 Production of Refractory Metal Concentrates in Canada in 1982 [26]

Concentrate	Quantity of metal contained (tonnes)
Pyrochlore	870 of Niobium (Nb)
Scheelite	3 410 of Tungsten (W)
Tantalite	41 of Tantalum (Ta)
Molybdenite	6 400 of Molybdenum (Mo)
Titanium	1 332 000 of Titanium (Ti)

In the past several years, substantial decrease in demand for refractory metal concentrates, due to the recent recession, caused the production of a number of mining operations to decrease, while quite a few were shut down completely [63]. At the same time, markets in Canada for specialty (refractory) metals and their ferro-alloys are supplied mostly from imports. Table 4-2 shows Canadian consumptions, average price and added value for ferro-alloys of niobium, molybdenum, vanadium, tungsten, and chromium as well as titanium sponge, in 1982.

Table 4-2 Canadian Consumption, Average Price and Added Value of Selected Ferro-Alloys and Titanium Sponge in 1982
[in kilograms of contained metal]

	Consumption kg/yr	Average Price US$/kg	Added Value US$/kg
Ferroniobium Std. Grade 65% Nb	130 000	13.77	3.55
Ferromolybdenum 70% Mo	200 000	20.70	3.10
Ferrovanadium Caravan Grade 11% - 12% C	400 000	14.20	2.10
Ferrotungsten 87% - 93% W	6 000	28.10	14.78
Titanium Sponge	N/A	12.10	11.70
Ferrochrome 66% - 70% Cr 5% - 6.5% C	15 900 000	1.10	0.89

Source: CEA Research Report No. 126 U 312, March 1984

Application of plasma technology for production of specialty (refractory) metals and their ferro-alloys could probably be the area which in the relatively short term would offer promising possibilities for the new indigenous Canadian industry due to lower cost of electricity in Canada and high added value of the metals and their ferro-alloys (compared to the cost of concentrates).

A brief discussion of plasma technology state-of-the-art development for production of ferro-alloys and specialty (refractory) metals is presented below. The presentation is limited to those ferro-alloys and metals which might be produced based on previously mentioned Canadian resources containing refractory metals. Also titanium dioxide pigment production using plasma is outlined in this chapter.

4.1 FERROVANADIUM

The fly ash derived from Alberta oil sands contains substantial amounts of vanadium pentoxide (V_2O_5). The amount of vanadium associated with the current production of two oil-sands plants - Suncor and Syncrude, is approximately 5.5 t/d (2000 t/yr) [62]. As Western countries consume above 16 000 t/yr (including Canadian consumption of about 300 t/yr) of vanadium, its production from oil sands could not only cover Canadian needs, but could also make a substantial impact on the world vanadium market.

In the Suncor oil-sands plant, the bitumen produced during extraction is upgraded by thermal cracking where about 22% of bitumen becomes coke. The coke contains approximately 3 wt% "ash" including vanadium. About 80% of this coke is crushed and burned in boilers. The remaining 20% is sent to storage. The typical composition of fly ash from the boilers is presented in Table 4-3 [62].

Table 4-3 Fly-Ash Composition (Suncor Oil-Sands Plant)

Composition	C	V_2O_5	TiO_2	NiO	Fe_2O_3	Al_2O_3	SiO_2	CaO	S	NaO_2
wt %	30	5	3	1.5	6	20	30	2	2	0.5

Several developments of plasma technology for production of ferrovanadium have been carried out in recent years, particularly at Bethlehem Steel, U.S.A., Noranda Research and University of Toronto, Canada.

Bethlehem Steel, U.S.A. has carried out research and development on ferrovanadium production from vanadium pentoxide using their 100-kW and 500-kW "falling-film" DC plasma reactors [31].

The best experimental results achieved with the 100-kW plasma reactor are presented in Table 4-4.

Table 4-4 Experimental Results on Ferrovanadium Production in 100-kW Bethlehem Steel Falling-Film DC Plasma Reactor [31]

Operating Conditions	
Feed	107 lb/h
	76% V_2O_3
	24% coke (50%, -500 mesh)
Carrier gas	165 scfh argon
Heater stabilizing gas	395 scfh argon
	440 scfh hydrogen
Initial iron heel in crucible	5.7 lb Sorel pig-iron
Results	
Time on feed	48 min (plus 26 min post-heat)
Input power	124 kW
current	565 amp
voltage	211 volts
Gas enthalpy	0.226 kWh/ft^2 equivalent H_2
Heater efficiency	80.4%
Energy consumption	2.5 kWh/lb vanadium (3.9 kWh/lb with post-heating)
Product consumption	75% to 88% vanadium (3 pours)
Vanadium recovery as metallics	90%

In the above tests, low-melting-temperature V_2O_5 was pre-reduced to the higher melting-temperature V_2O_3 to prevent plugging of the ore feed ports experienced when feeding V_2O_5 directly into the reactor.

Table 4-5 Data Summary on Ferrovanadium Production in 500-kW Bethlehem Steel Plasma Reactor [31]

Test No.	1	2	3	4	Extended Run
Gross Power, kW	451	416	441	424	409
Gross Enthalpy, kW/ft^2 equivalent H_2	178	168	179	169	175
Arc Head Efficiency, %	83.7	81.2	85.0	83.2	79.8
Feed Period, h	1.0	1.0	.75	1.1	7.4
Feed Rate, lb/h Vanadium	109	158	149	158	117
Vanadium yield, %	74.0	88.9	84.5	88.6	80.9
Energy Consumption, kWh/lb Vanadium	4.1	2.6	3.0	2.7	3.5
Product, %					
Vanadium, V	52.0	53.1	48.2	55.2	42.9
Iron, Fe	41.8	40.3	45.8	36.1	53.0
Carbon, C	5.2	3.9	4.6	6.8	2.9
Oxygen, O_2	0.2	1.0	0.4	0.35	0.95
Silicon, Si	0.3	0.35	0.38	0.32	0.32
Manganese, Mg	0.01	0.15	0.04	0.05	0.02
Sulphur, S	0.31	0.28	0.29	0.25	0.44
Copper, Cu	0.004	0.008	0.011	0.02	0.02

Hydrogen and argon were used as a stabilizing gas, argon was also used as the feed carrier gas. The initial iron heel was formed in the crucible by melting 2.6 kilograms of Sorel pig-iron. The electricity consumption was 5510 kWh/t (2.5 kWh/lb) of vanadium without taking into account "post-heat" requirements (about 8595 kWh/t of vanadium including energy consumption for "post-heating"). A "post-heat" period during which the heater was kept on after the solids feed was turned off was required to completely melt the crucible contents. The product was mostly vanadium carbide. The data summary on ferro-vanadium production in the 500-kW Bethlehem Steel plasma reactor is presented in Table 4-5.

Production of ferrovanadium from vanadium pentoxide with iron and carbon at a lower scale using the Noranda configuration DC plasma reactor (see reactor description in Chapter 2) was reported by W.H. Gauvin. [26]. A ferrovanadium containing 79.4% vanadium, 18% iron and 0.6% carbon was produced during these tests. The high vanadium and low carbon contents of the ferrovanadium obtained are particularly suitable for steel production.

At the University of Toronto, investigation has been carried out using the extended-arc flash AC plasma reactor (EAFR) for the production of ferrovanadium and ferronickel from oil-fired boiler fly ash [29].

The analyses of the original sample of fly ash (designated Ash 1), the ash obtained by oxidizing carbon in the original sample (Ash 3) are presented in Table 4-6 along with the bottom ash (Ash 2) obtained during carbon oxidizing of the original sample.

Table 4-6 Ash Analyses [29]

Composition wt %	Ash 1	Ash 2	Ash 3
Carbon, C	75	-	0.65
Sulphur, S	5	-	3.42
Vanadium Pentoxide, V_2O_5	12	31	42.43
Nickel Oxide, NiO	2	5	7.64
Iron Oxide, FeO	3	6	27.52
Magnesium Oxide, MgO	-	35	2.01
Silicon Dioxide, SiO_2	-	-	2.42
Calcium Oxide, CaO	-	-	2.50
Alumina, Al_2O_3	-	-	1.09

The original fly ash sample was porous low density material. Ash 3 contained denser material and was richer in metallic values. Ash 2 has intermediate density [29].

In the two-step tests, ferronickel was produced first using Ash 3 mixed with reductant (see Table 4-7). The feed was batch-charged into the single-phase AC EAFR with a power input of 15 kW. By limiting the carbon content in the charge it was possible to reduce all the nickel selectively. After 30 minutes of heating, lime and silica were added to form a V_2O_5-rich slag. After a further 30 minutes the slag and ferronickel were tapped from the furnace.

Table 4-7 Typical Test Data for Production of Ferronickel from Pre-treated Fly Ash (Ash 3) in 15-kW EAFR [29]

Test No.	Feed				Metal Recovered			Slag	
	Ash 3	Reductant	Lime	Silica	Weight	Analysis		Weight,	V_2O_5 wt %
	g	g	g	g	g	V wt %	Ni wt %	g	
1	1 500	175 anthracite	250	250	210	1.14	33.0	1 260	35.3
2	1 500	150 petroleum coke	250	100	225	1.21	33.5	1 190	38.2
3	1 500	125 petroleum coke	250	200	160	0.58	37.6	1 250	33.1
4	1 500	100 petroleum coke	250	100	125	0.36	44.5	1 290	30.6

In the second step, the obtained V_2O_5-rich slag was ground to -65 mesh and further processed in 25-kW three-phase AC EAFR with a magnesia lining. The reductant was mixed with the ground slag and batch-charged into the furnace. The test results are shown in Table 4-8.

Table 4-8 Conditions and Data for the Production of Ferrovanadium from the Vanadium Oxide-Rich Slag Obtained During Ferronickel Production [29]

Test No.	V_2O_5 Slag Weight, g	Reductant Weight, g	Metal Recovered, g	Theoretical Metal Weight, g	Vanadium Recovery wt %	Metal Analysis wt % V
5	1 260	400 petroleum coke	350	445	78.7	61.3
6	1 190	450 petroleum coke	380	455	83.5	65.6
7	1 250	500 petroleum coke	360	415	86.7	57.1
8	1 290	500 anthracite	340	395	86.0	52.9

It can be seen that, from the pre-treated fly ash having higher density and metals content, ferronickel and ferrovanadium may be produced separately in a plasma two-step process. Nickel contents in the range of 30% to 40% were achieved. In the ferro-vanadium produced, vanadium contents were in the range of 50% to 60%. Metals recovery, both in nickel and vanadium were over 80%.

Also, one-step production of ferro-nickel-vanadium in 25-kW and 70-kW EAFR were investigated in the cited work. In the 70-kW EARF tests with anthracite used as a reductant, 90.3 to 95.8 wt%

metal recovery (43.2 to 62.5 wt% vanadium) have been achieved. The average energy consumption in the 70-kW reactor was equivalent to about 16 500 kWh/t of ferro-nickel-vanadium [29]. It was also found that while nickel oxide was completely reduced before reaching the hearth zone (due to relative instability of NiO), the liquid-liquid (metal-slag) contact was required to reduce stable oxides such as V_2O_3 to ferro-alloys.

Analysis of the above results (despite the relatively low-scale of the experiments) gives expectations that further development towards commercial production of ferrovanadium from fly ash available as a by-product from Alberta's oil sands - synfuels plants is the challenging opportunity for plasma technology application in Canada. A techno-economic assessment of ferrovanadium production from this fly ash using plasma versus other known methods (which is beyond the scope of this study) is recommended to define the economic potential of this plasma technology application.

4.2 FERROCHROMIUM

The most extensive development towards commercial production of ferrochromium using plasma technology is being carried out in South Africa by the Council of Mineral Technology (MINTEK) in conjunction with Middelburg Steel and Alloys (MS&A), and SKF Steel in Sweden.

In 1979, **MINTEK and MS&A** undertook an experimental investigation on smelting of high carbon ferrochromium from Transvaal chromium ore fines. Fine carbonaceous reducing agents, such as cheap coal fines or char were used in these experiments carried out in a 1400 kVA transferred-arc Tetronics plasma furnace. Argon was used as a plasmagen gas. A total of 13.8 tonnes of feed

materials were processed during this investigation to produce 5.7 tonnes of high carbon ferrochromium at power input up to 750 kW. High carbon ferrochromium (about 56% chromium, 34% iron and 5.5% carbon) was successfully produced by addition of suitable fluxes (quartz or silica and lime) and coal fines as reducing agent (fixed carbon 51% and 54%, volatile matter 33% and 37%, ash 10% and 14%) to the chromite fines (44.6% Cr_2O_3, Cr/Fe ratio 1.69). Chromium recovery of 96%, energy consumption of 3108 kWh/t of metal in ladle and low slag-to-metal ratio of 1.02 have been achieved in these experiments [42].

Following the above investigation carried out at Tetronics Ltd., U.K., a 3.2-MVA pilot-plant plasma facility has been installed at MINTEK to define the amenability of various local ores, chromite in particular, to processing with plasma technology. Also, smaller plasma furnaces have been used by MINTEK for these tests. The MINTEK 3.2-MVA furnace is designed to allow the use of either a water-cooled plasma torch or hollow graphite electrode. For both of these plasma-generating devices, the positive pole of the DC supply was connected to the bath of the furnace and the negative pole was connected to the plasma torch or hollow graphite electrode.

These two plasma devices represent the extremes of plasma development philosophies. The water-cooled, transferred-arc torch is complex and its initial capital cost is relatively high, but consumable cost (i.e., cathode wear) is lower compared to graphite electrodes. On the other hand, the hollow graphite electrodes are a major consumable item (about 2 to 3 kg/t of metal treated) and require a substantially larger diameter of electrode for high-current operation. The hollow graphite electrodes, however, can be operated easily using an AC power supply rectified by a diode bridge. This type of system can

utilize the on-load, tap-changing transformers that are used for conventional submerged-arc electric smelting furnaces.

The 100-kVA experimental plasma furnace developed and used at MINTEK is shown in Figure 4-1 [64]. The furnace employs a hollow graphite electrode (50 mm dia., a 10 mm bore) through which a mixture of argon and nitrogen was passed as the plasmagen gas at rates of 5 to 50 L/min. The feed (0.2 to 6.0 mm particles) was fed at rates of 5 to 70 kg/h through the single-feed port.

Based on the positive results of plasma tests at MINTEK, the Middelburg Steel and Alloys Company has commissioned a 20-MVA transferred-arc plasma DC furnace with hollow graphite electrode at the Krugersdorp division of Middelburg Steel and Alloys (MS&A).

The furnace has been in operation since the end of 1983 and several thousand tonnes of ferrochromium have already been produced [64]. The furnace was developed and supplied by ASEA, Sweden based on ASEA DC arc furnace development for direct iron-ore smelting process ELRED (see ELRED Chapter 3).

It was found that the mechanism controlling the chromite reduction process is dissolution of iron and chromium oxides in the slag layer of the liquid metal bath and then oxides reduction by carbon in the coal (the reductant) to yield the metal and also metal carbide (so-called "in-bath" reduction). Injection of the ore/reductant/slag powder mixture through the plasma arc resulted in partial (non-complete) "in-flight" pre-reduction of chromite [64,65]. Therefore, for higher flexibility of commercial plasma furnace operation at MS&A, the feed is introduced through the feed ports, while plasmagen gas (argon) is injected through the hollow graphite electrode (see Figure 4-2).

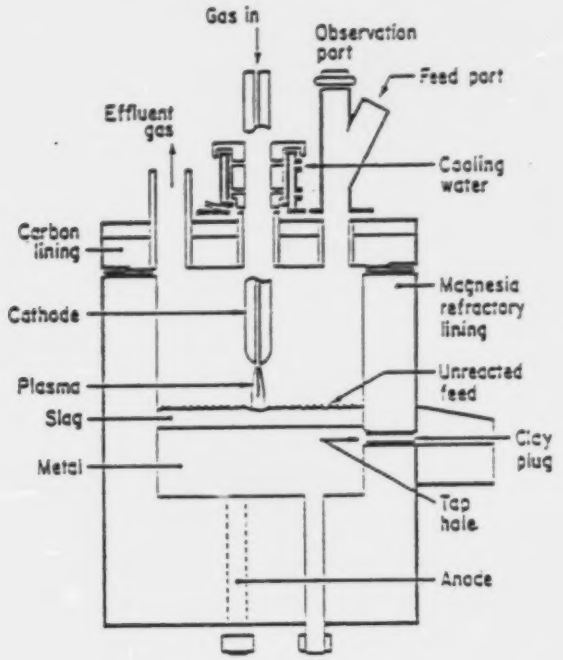

Figure 4-1 MINTEK 100-kVA Plasma Reactor

Techno-economic data on operation of the 20-MVA furnace are not available yet. Economic assessment made earlier (1977), however, of the plasma ferrochromium process in an open-bath plasma furnace has predicted about 20% to 30% reduction of the product cost as compared to a conventional electric furnace [66]. This is mostly due to elimination of agglomerating plant, the use of low-cost coal fines instead of coke or char, high chromium recoveries and lower electrode costs.

SKF Steel Engineering, Sweden, has developed a coke-filled low-shaft plasma furnace with the injection of compressed recycled process gas with the ore/slag/reductant mixture in non-transferred-arc DC plasma torch for production of ferrochromium. The process is known under the trade name PLASMACHROME [67,68]. This process was successfully demonstrated by SKF Steel in their Hofors pilot plant [67].

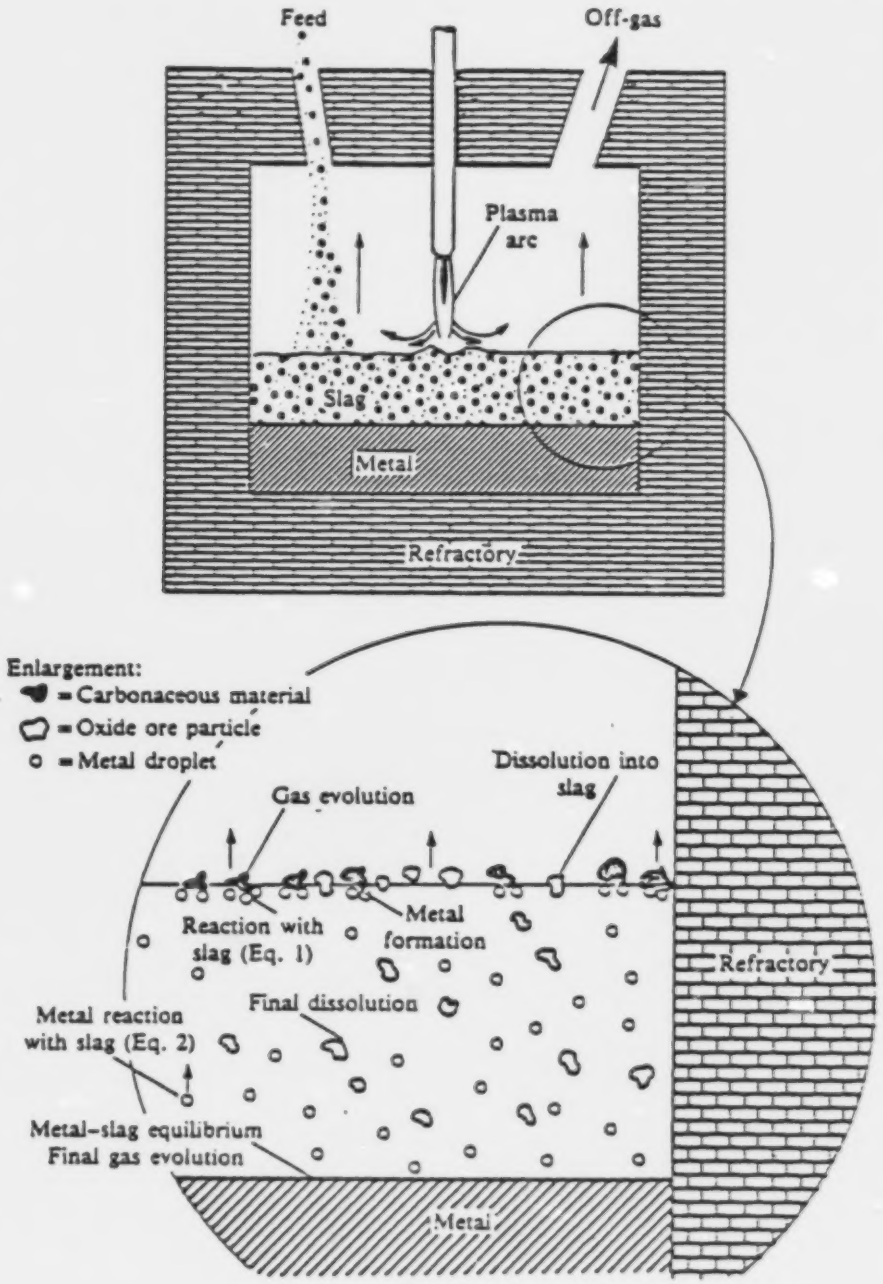

Figure 4-2 Schematic View of An Open-Bath Plasma Process

The composition of chromite used, and metal analyses obtained during the PLASMACHROME pilot-plant tests are presented in Tables 4-9 and 4-10 respectively. The energy consumption during the pilot-plant tests were in the range of 5300 to 5800 kWh/t of ferrochrome. The first commercial PLASMACHROME plant, designed capacity 78,000 t/yr ferrochrome, is being built in Malmo, Sweden.

As already mentioned (see Chapter 2), SKF Steel also developed a plasma process for recovery of several metals including chrome and iron, as well as zinc and lead (low-boiling temperature metals) from steel waste dust. A condenser for the recovery of these low-boiling temperature metals is added on the process gas recycle line. The process is known under the trade name PLASMADUST. In 1982, SKF Engineering signed a contract to supply a turnkey PLASMADUST plant with design capacity of 70 000 t/yr of dust, to a specially formed company SCANDUST which owns and will operate the plant. The plant's plasma furnace is equipped with three 6-MW SKF plasma torches. The plant is located in Landskrona, Sweden, and has been on trial runs since March 1985 [69].

Table 4-9 Chromite Ores Used in PLASMACHROME Pilot-Plant Tests

Component, %	1	2	3	4
Cr_2O_3	44.3	49.0	54.1	55.0
FeO	24.7	17.8	15.6	13.5
SiO	2.0	3.0	2.6	1.1
MgO	9.3	13.9	14.4	13.6
Al_2O_3	13.7	11.2	8.2	11.8
CaO	0.2	0.4	-	0.1
Cr/Fe	1.58	2.43	3.06	3.59

Note: In all cases a fine-grained chromite (- 1 mm) was used. As reducing agents in the tests, 30% metallurgical coke (86% fixed carbon) and 70% coal (32% volatile matter, 0.9% sulphur and 12% ash) were used. The fluxing agents used for slag forming were burnt lime (92% CaO) and silica sand (95% SiO_2).

Table 4-10 Analyses of Metal Obtained in PLASMACHROME Pilot-Plant Tests

Component, %	1	2	3	4
Cr	45.9-54.3	61.3-63.0	66.1-66.9	66.4-69.2
C	5.4-8.2	6.7-9.5	6.0-8.1	6.1-8.7
Si	0.11-2.14	0.19-1.23	0.21-1.42	0.22-1.61
S	0.006-0.016	0.001-0.016	0.003-0.019	0.003-0.026
Cr yield	65-94	88-96	87-92	86-91

4.3 FERROMOLYBDENUM

Ferromolybdenum and molybdic oxide are two of the most important additives for the production of specialty and high-strength, low-alloy (HSLA) steels.

The conventional process for the production of molybdenite concentrate (typically 57% Mo, 38% S) includes roasting, during which molybdic oxide (MoO_3) and sulphur dioxide are produced, followed by scrubbing out of sulphur dioxide, and of molybdic oxide reduction to ferromolybdenum (containing 50%-70% Mo) with ferrosilicon and aluminum [70].

Plasma decomposition of molybdenite has the potential of a considerable simplification of the conventional technology and also would avoid the related environmental problems (air pollution by sulphur dioxide).

The technical feasibility to decompose MoS_2 using transferred-arc DC plasma was proven by R. Munz and W. Gauvin in 1975 [71]. The conversion achieved at that time, however, with argon as a plasmagen gas was not high enough to reduce the sulphur content in the product metal to the value required by the steel industry (0.15% S max.).

In 1981, after several years of research and development work carried out at The Noranda Research Centre, Pointe Claire, Québec, Canada the conditions were defined under which the sulphur content in the product was consistently reduced below the target 0.15%.

The best results achieved using the Noranda configuration plasma reactor with nitrogen as a plasmagen gas were 99.96% decomposition efficiency (0.03% S) at an energy consumption of 12 kWh/kg of molybdenum in the feed [70].

A conceptual plant design for production of 2268 t/yr of contained molybdenum was carried out by the Noranda Research Centre in collaboration with an independent engineering company based on the above experiments. The simplified flowsheet of this conceptual plant is shown in Figure 4-3 [70, 72]. The process comprises drying of the molybdenite concentrate in the fluidized-bed dryer, and feeding it pneumatically with nitrogen carrier gas to two 2-MW plasma reactors. The reactor product is tapped molten (2200°C) for refining and composition adjustment in a 1500-kW induction furnace. To produce a lower melting-point ferromolybdenum, alloy steel is added; lime-fluorspar flux is used for desulphurization and mill-scale for decarburization of the product. The product containing about 50% molybdenum is crushed and screened to market specifications.

The reactor off-gas is cooled from 2300° to 325°C by quenching with a recycle gas and then in a cooler before entering a baghouse. The baghouse is operating above the sulphur vapour condensation temperature. The sulphur is subsequently condensed from the clean gas, and the residual non-condensable sulphur species (H_2S, CS_2 and COS) are combusted to SO_2 which is lime-neutralized before discharge of the effluent gas to atmosphere [70]. The preliminary cost estimate of this plant is presented in Section 4.7.

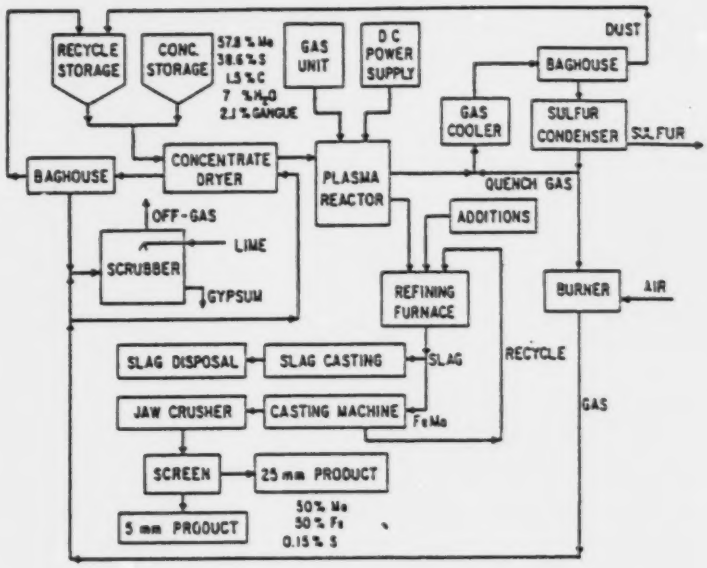

Figure 4-3 Simplified Flowsheet for Plasma Production of Ferromolybdenum from Molybdenite Concentrate.

4.4 NIOBIUM AND TANTALUM

An experimental program on plasma production of ferroniobium is currently in progress at McGill University, Montréal, Québec, Canada, following promising techno-economic assessment on feasibility of carbothermic reduction of pyrochlore to ferroniobium in a thermal plasma reactor [73].

Carbothermic reaction of tantalite, Ta_2O_5 at a temperature of 3400 K, to yield 99.9% Ta with 50 ppm of oxygen and 400 to 500 ppm of carbon was also recently reported [74]. Plasma production of these two refractory metals or their alloys, however, is still in the laboratory research stage and cannot be considered for industrial applications at the present time.

4.5 ZIRCONIUM AND TITANIUM

Efforts to reduce ZrO_2 directly to the metal have not been successful. Commercial processes to produce zirconium and titanium metals in so-called "sponge" form involve conversion of the metal oxide to the halide (usually chloride) which has low melting (or sublimation) and boiling points, and then reduction of the halide to the metal sponge. The conventionally used commercial processes are quite complicated and comprise a sequence of many steps. The block diagram of the last stage of a commercial process to produce zirconium sponge from zirconium tetrachloride, $ZrCl_4$ using magnesium as a reductant, (known as the Kroll process) is presented in Figure 4-4. Titanium metal sponge is also produced on a commercial scale from titanium tetrachloride, $TiCl_4$ either by reduction with magnesium (i.e., by the Kroll process) or by reduction with sodium, (the Hunter process).

Since early 1981, researchers at both the Industrial Materials Research Institute (IMRI), Boucherville, Québec, and McGill University have been developing plasma production of both zirconium and titanium metals using the Noranda configuration plasma reactor to replace the costly conventional Kroll process.

Figure 4-5 presents the block diagram of the proposed plasma process for production of zirconium. The technical feasibility of such a process was demonstrated on a laboratory scale. There has been little incentive, however, to pursue the development of plasma production to nuclear zirconium because of the small market. Plasma production of zirconium metal without removal of naturally occurring hafnium still would have a substantial market since the presence of hafnium does not affect the high strength and corrosion resistance of the metal [33]. At the same time,

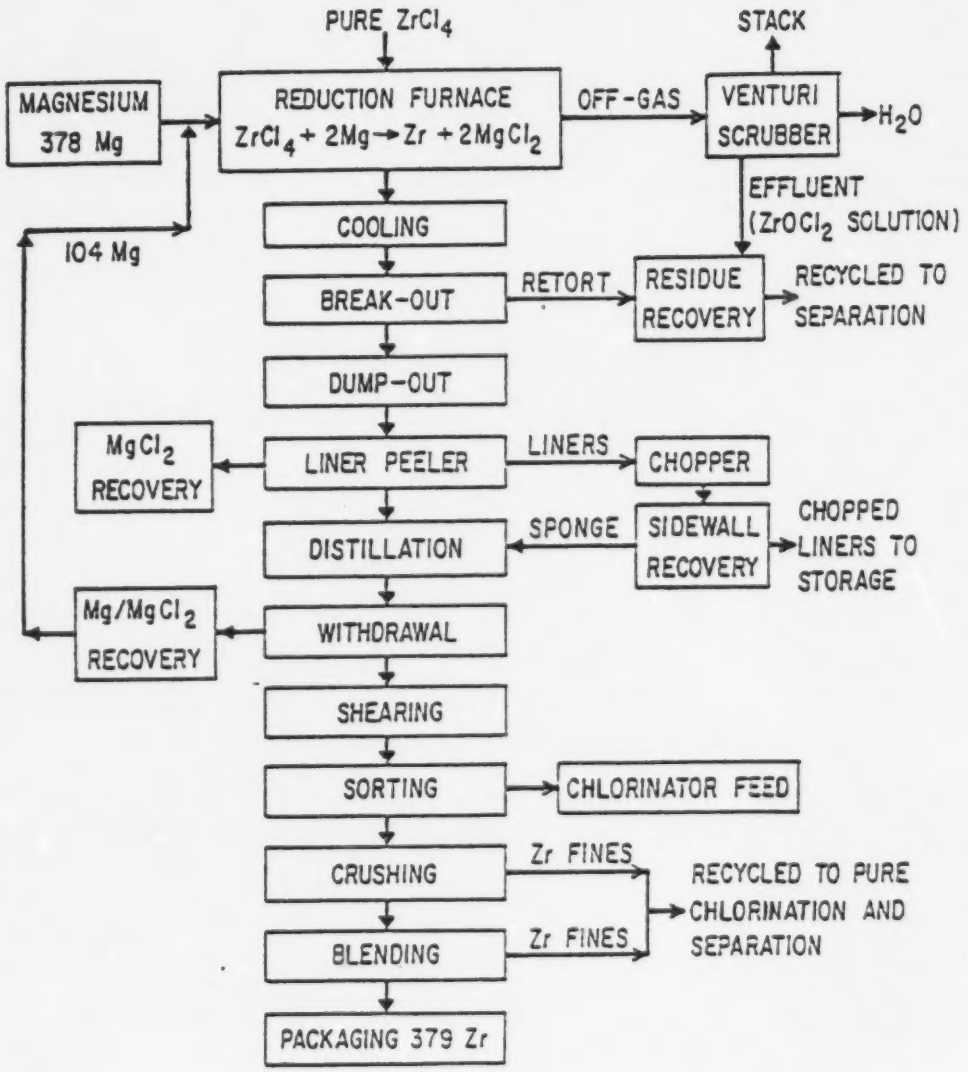

Figure 4-4 Block Diagram of Kroll Process for Last Stage of Zirconium Sponge Reduction

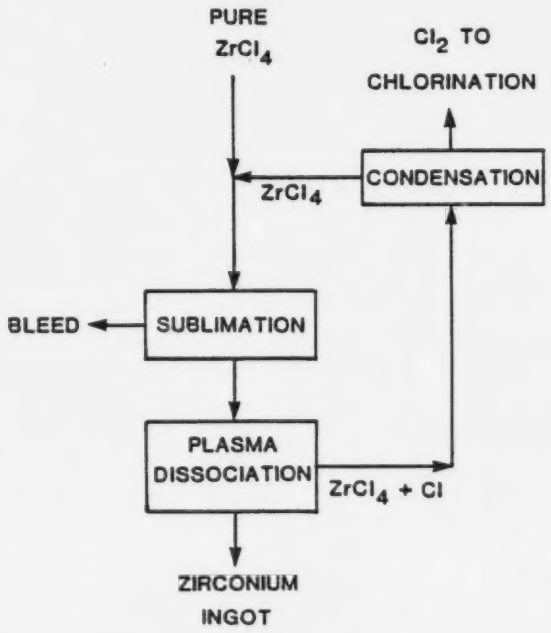

Figure 4-5 Block Diagram of Zirconium Plasma Process

the estimated cost for plasma production of zirconium containing hafnium would be much lower than that of zirconium sponge produced by the commercial Kroll process, as was shown by the McGill University Plasma group based on the results of laboratory investigations [30].

The McGill University Plasma Group has investigated the production of $ZrCl_4$ by the chlorination of ZrO_2 in the presence of chlorine plasma. A dense metal was produced instead of sponge [75,76].

The plasma production of titanium metal is being carried out at McGill University - IMRI in a manner identical to that described above for zirconium metal. Also production of secondary products, such as titanium carbides, titanium nitrides and other alloys in the form of powders which are required for plasma spray coating is being investigated [33].

For a number of years now, the Electricity Council Research Centre, Chester, England has been investigating a single-stage, gas-phase reduction of $TiCl_4$ with sodium in a hydrogen plasma at temperatures up to 2300 K. Metallic titanium substantially free of chlorides was successfully produced in a 30-kW plasma furnace. Difficulty, however, has been experienced in controlling the addition of the feed materials [77]. Following the same idea and applying the technique developed for production of pure silicon, Westinghouse demonstrated reduction with sodium in hydrogen/argon plasma to $TiCl_4$ in a 40-kW laboratory plasma unit. Titanium metal in various forms was produced. The sodium chloride by-product was removed as a vapour, thus allowing continuous operation [30].

4.6 TITANIUM DIOXIDE

Titanium dioxide pigment production is of great importance for Canada since, as already mentioned, Canada possesses abundant resources of ilmenite ore containing 14% TiO_2 and 37% Fe on average. Based on these resources, "Fer et Titane" (QIT) in Québec is one of the major exporters to the U.S.A. of titanium "slag" containing about 85% to 96% TiO_2 as a feedstock for titanium dioxide pigment production.

Titanium dioxide pigment is currently produced using two methods, the classic sulphate process and the more recent chloride process. In the sulphate process, titanium "slag" is reacted with sulphuric acid and the resulting solution of titanyl sulphate is hydrolized to form a hydrated oxide which is calcined in a rotary kiln to crystalline titanium oxide. In the chloride process, titanium ore with high titanium content (rutile) is chlorinated in the presence of carbon to produce

liquid titanium tetrachloride which is then purified by distillation and further oxidized in the vapour phase to titanium dioxide. The requirements for oxidation of titanium tetrachloride (rapid rise of the temperature of the reactants to that required for reaction to occur, followed by a quench to prevent excessive particle growth and formation of TiO_2 deposits on the reactor walls) may be easily net by thermal plasma technology. A commercial thermal plasma oxidation process has been developed by Tioxide U.K. and applied to the oxidation of titanium tetrachloride in the company's plant at Greatham, England where the chloride process is used [78]. The Tioxide Canada plant, at Sorel, Quebec consumes about 15% of QIT titanium "slag" production as a feedstock. The sulphate process is used at this plant; therefore, the plasma oxidation of titanium tetrachoride does not apply.

4.7 ECONOMIC CONSIDERATIONS

Plasma production of each ferro-alloy or specialty (refractory) metal would require a separate technology with specific techno-economic features which will affect the capital and production costs.

A preliminary plant design for plasma production of ferrovanadium from vanadium pentoxide (about 450 t/yr of contained vanadium) has been done by Bethlehem Steel Corporation, U.S.A., based on operation of their 500-kW falling-film DC plasma reactor [31]. No data on capital or operations costs, however, are available. Also, no details are available yet on plant design and operating cost of plasma ferrochromium production at Middelburg Steel and Alloys, South Africa, discussed in Section 4.2 above.

More detailed information was published concerning design and economics of a conceptual plant for plasma production of ferromolybdenum which was carried out by Noranda Research Centre, Québec, Canada in collaboration with an independent engineering company [70].

The simplified flowsheet of the plant has been presented and discussed in Section 4.3.

The design basis assumed for this conceptual plant includes [70,72]:

Annual production of 5 million lb of molybdenum contained in the product by direct plasma decomposition of molybdenite concentrate. Assumed concentrate composition was 57% Mo, 38.1% S, 2.2% SiO_2, 0.7% other gangue, 1.5% oil, 0.5% free carbon, 7% moisture before drying, 0.1% moisture in the dried concentrate. The product should contain 50% Mo*. The carbon and sulphur contents should not exceed 0.1% C and 0.15% S.

Nitrogen is used as a plasma gas at the rate of 1 kg/1.5 kg of feed to the plasma reactor. The gas from the sulphur condenser should contain not more than 0.05% sulphur vapour.

Low-carbon steel to produce a ferromolybdenum alloy having a low melting point, lime-fluorspar flux (4 CaO: 1 CaF_2) for sulphur removal and mill scale (Fe_3O_4) for decarburization are used at the refining stage. The total refining slag is about 0.15 kg/kg of refined molybdenum.

The capital cost estimate and total investment of the plant are presented in Table 4-11.

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* The current market specifications require 67% Mo for Grade 1 and 62% Mo for Grade 2 contained in FeMo product with 0.10% S maximum [79].

Table 4-11 Preliminary Capital Cost Estimate and Total Investment for Plasma Ferromolybdenum Plant

[Basis: 4.54 million kg/yr FeMo, 50% contained Mo]

Item	Cost, Canadian Dollars, March 1985	
	$	%
Concentrate Drying and Storage	200 000	1.34
Plasma Reactors (Incl. Feeding, Tapping, DC Power, and Nitrogen Supply)	2 196 000	14.73
Plasma Reactor Off-gas Handling	665 000	4.46
Off-gas Sulphur Fixation	1 476 000	9.90
Metal Handling: Refining/Casting/Crushing	2 332 000	15.65
Site Development	419 000	2.81
Civils/Structurals	1 217 000	8.17
Mechanical Services	813 000	5.46
Electrical Supply and Instrumentation	1 711 000	11.48
Mobile Equipment	168 000	1.13
	11 197 000	
Contingency	2 239 000	15.02
Total Installed Plant Cost (TIPC)	13 436 000	
Start-up Expenses	403 000	2.71
	13 839 000	
Working Capital*	403 000	2.71
Land*	660 000	4.43
Total Investment	14 902 000	100.00

* Non-depreciable items

Table 4-12 Preliminary Direct Operating Cost Estimate for Plasma Ferromolybdenum Plant

[Basis: 4.54 million kg/yr FeMo, 50% contained Mo]

Item	Cost, Canadian Dollars, March 1985	
	$ per year	%
Natural Gas	79 890	1.64
Scrap Steel	273 800	5.64
Limestone	25 150	0.52
Lime Flux	35 800	0.74
Mill Scale (Fe_3O_4)	13 350	0.27
Fluorspar Flux	22 200	0.46
Silica Sand	970	0.02
Electricity	872 700	17.97
Make-up Water	23 100	0.47
Nitrogen	35 810	0.74
Product Drums	375 000	7.72
Labour and Supervision	1 173 400	24.16
Operating Supply	247 000	5.08
Maintenance Cost	403 000	8.30
Refractory Maintenance	312 600	6.44
Property Taxes and Insurance	302 300	6.22
Overhead and Administration	661 150	13.61
Total Direct Operating Costs	4 857 220	100.00

The annual direct operating cost breakdown is shown in Table 4-12. The data have been derived on the basis of above mentioned Noranda plant design and financial assumptions, economic criteria, and unit prices of the materials and other components presented in the Appendix.

All costs are given in March 1985 Canadian dollars, taking into account time cost differences (cost indexes), Canadian conditions as well as currency exchange rate and duty, where required.

Analysing the data summarized in Table 4-11, it may be seen that the cost of plasma reactors (including feeding, tapping, DC power and nitrogen supply systems) comprises about 15% only of total capital investment required for the plant. A contingency as high as 20% of the TIPC (about 15% of the total investment) was assumed since the plasma decomposition of molybdenite had not yet been proven commercially.

As shown in Table 4-12, the cost of electricity comprises only about 18% (at $0.03/kW) of the direct operating plant costs (about 15% at $0.024/kW).

The estimated product cost is Can. $14.88 (US $10.94)/kg Mo contained in ferromolybdenum, 50% Mo. The 1985 market price for standard grades of ferromolybdenum is US $11.88/kg Mo in FeMo [79].

CHAPTER 5

THERMAL PLASMA IN MELTING/REMELTING

5.0 THERMAL PLASMA IN MELTING/REMELTING

Melting/remelting operations are usually carried out in gas or electric-heater furnaces.

Electric-arc furnaces are widely used in Canadian industries, including steelmaking based on scrap, etc. In 1982, about 200 MW of electric-arc furnace capacity was installed in Canada, all under 30 MW power [72]. Although relatively efficient from an energy point of view, electric-arc furnaces have some shortcomings which are inherent to their fundamental principles of operation, such as the high cost of refractory and electrodes replacement (16% and 24% of the total operating cost respectively) [80]. The operation is a batch multi-step process where each step requires a different level of supplied power to the electrodes. Electric furnaces are restricted as to the particle size and physical characteristics of the feed material: they certainly cannot accept gaseous or finely divided materials which may be the preferred state of the feed in certain applications. Recent developments in plasma furnace applications have clearly shown that these furnaces have distinct advantages over electric-arc furnaces.

In 1962, Linde Division of Union Carbide had demonstrated for the first time the melting of primary metals using their plasma furnace discussed in Section 2.2. The results obtained by Linde indicated that higher quality steel could be produced compared to that obtained using conventional technology [30].

At present, plasma melting/remelting installations are in operation in several countries at pilot-plant and commercial-scale levels.

A comparison of the actual performance of submerged-arc electric furnaces and plasma furnaces, presented by W. Lugscheider of Voest-Alpine, Austria [81] and based on the operation of a 10-tonne plasma furnace in Freital, F.R.G. over 10 years has indicated substantial advantages of the plasma furnace in melting/remelting operations. Among these advantages are the following [36, 43, 82]:

- Higher melting efficiency.
- Superior recovery of the alloy metals contained in the scrap and of those added in the melt.
- Minimum contamination and loss of volatile constituents.
- High quality of the product.
- Complete control of atmosphere (inert of reactive).
- Suppression of noise to a level of about 70 to 80 dB.
- Elimination of shock loading of the electric power transmission (no flicker).
- No carbon contamination from electrodes.
- Lower capital investment (up to 30%) compared to a modern Ultra High Power (UHP) electric-arc furnace system.

Some of the plasma melting/remelting installations based on the application of currently available plasma furnaces among those described in Chapter 2 are presented below:

5.1 PLASMA MELTING/REMELTING INSTALLATIONS

G.D.R. AND AUSTRIA

As discussed in Chapter 2, several plasma melting/remelting DC furnaces with torches (cathodes) installed in the sidewalls, ranging in capacity from 5 to 30/40 tonnes have been in operation at Freital for a number of years now. Also, a 45/60- tonne plasma furnace of this type is in operation at Linz, Voest Alpine, Austria.

Alloying elements yield and iron losses obtained during test runs of melting medium and high-alloy steels in plasma and electric-arc furnaces [with and without argon-oxygen converter (AOD)] at Freital are presented in Table 5-1 [36,43]. The melting-down energy for non-alloy and alloy steels, including both the experimental results obtained and performance data predicted by the process developer are shown in Table 5-2 [36].

It can be seen (Table 5-1), that alloying metal yields are substantially higher in plasma melting, while iron losses are lower (e.g., iron loss is from 1% to 2% in plasma melting, 2% to 4% in electric-arc AOD furnace, 4% to 6% without AOD). The plasma melting-down energy (Table 5-2) is between 500-800 and 430-480 kWh/t depending on the capacity of the furnace and input power in the range of 1-5 to 40-50 tonnes and 2-6 to 20-25 MW respectively. The estimated (predicted) melting-down energy for 50- to 100-tonne plasma furnaces (input power 25 to 40 MW) is below 400 kWh/t of steel.

Table 5-1 Alloying Elements Yield in Freital Plasma and Electric-Arc Melting Furnaces [36]

Alloying Elements	Plasma furnace %	Electric-Arc furnace AOD %	Electric-Arc furnace %
Cr	98 - 100	97	94 - 96
Ni	99 - 100	98	98
Mo	96 - 100	97	94 - 95
Mn	97 - 98	94	90 - 94
Si	96 - 100	90	88 - 91
Nb	98 - 100	85 - 90	74 - 77
W	97 - 98	96 - 97	85 - 90
V	95 - 97	93 - 97	83 - 85
Ti	75 - 88	65 - 70	45 - 65
Al	68 - 85	-	65 - 75
B	98 - 100	-	-
Fe	98 - 99	96 - 98	94 - 96

Table 5-2 Melting-down Energy for Non-Alloy and Alloy Steels in Freital Plasma Furnaces [36]

EXPERIMENTAL RESULTS				PREDICTED PERFORMANCE			
Capacity (tonnes)	Installed Power (MW)	Materials/ Alloys	Melting down energy (kWh/t)	Capacity (tonnes)	Installed Power (MW)	Materials/ Alloys	Melting down energy (kWh/t)
		Melting process- primary melting				**Melting process- reduction melting**	
1-5	2-6	special alloys	500-800	1-5(10)	2-4(6)	ferro-alloys ladle heating AOD, VOD	> 2500
5-10	4-8	special alloys special steels	470-700	10-50	5-10		
						Primary melting	
10-15	6-10	stainless steels non-alloy & medium alloy quality steels	470-550	50-70	25-30	non-alloy bulk steels	< 400
15-40	10-20	non-alloy and medium alloy quality steels, stainless steels	450-500	70-100	30-40	non-alloy bulk steels	< 400
40-50	20-25		430-480				

JAPAN

Daido Steel has used the plasma-induction furnace (PIF) (see Chapter 2, Figure 2-18) for melting a variety of special alloys, including magnetic and resistance alloys, stainless steel and superalloys. In a series of test runs for materials characterization purposes, several 500-kg charges of A-286 (iron-base superalloy) and Inco 718 (nickel-base superalloy) were melted in the Daido PIF and cast into 15.24 cm (6-in.) diameter, 152.4 cm (60-in.) long electrodes.

The plasma-induction melting and the resultant material evaluations reported by Daido Steel have indicated the following [82]:

- In general, plasma-induction melted material can be considered equivalent to that produced in the industrial-size vacuum-induction melting furnace.

- Plasma-induction melted material is superior to that produced in the electric-arc furnace and, subsequently, vacuum degassed.

- Plasma-induction melted material is suitable for the manufacture of castings of heat-resistant alloys and electrodes for remelting.

- Alloy recovery in the plasma-induction melted metal is greater than 95% as shown in Table 5-3.

- In general, the inclusions found in plasma induction melted heat-resisting alloys containing large amounts of titanium and aluminum are smaller than 10 microns in size.

Table 5-3 Alloy Recovery in Plasma Induction Melting Metal (Daido Steel Data) [82]

Element	Yield of Alloy Addition (%)
C	100.0
Si	99.0
Mn	98.0
Cr	100.0
Al	96.5
Ti	95.5
V	100.0
B	95.0
Nb	97.0

Application of PIF for melting/remelting requires, however, a considerable amount of expensive argon. To reduce operating costs, Daido Steel has developed a system for cleaning and recycling the argon gas [43].

SOUTH AFRICA

The Council of Mineral Technology (MINTEK) has carried out an experimental investigation of melting and refining of ferromanganese fines using the 1.4-MVA Tetronics furnace described in Chapter 2 and the 100-kVA MINTEK plasma furnace with graphite electrode (see details in Chapter 4). High carbon ferromanganese metal fines (about 180 kg) were remelted in the 100-kVA MINTEK plasma furnace. The fines (smaller than 6 mm in size) used in these tests were generated during sizing and handling of ferro-alloys. The chemical analysis of the feed material and the average analysis of ferromanganese produced are given in Table 5-4 [83]. The metal fines contain a small percentage of slag, which is not included in the analysis for manganese, iron, and silicon.

Table 5-4 Remelting of Ferromanganese fines in MINTEK 100-kVA Plasma Furnace: Chemical Analyses of the Feed and the Product [83]

Material	Feed (high-carbon ferromanganese, size <5 mm)	Product
Mn	73.7	75.3
Fe	13.5	17.1
Si	1.8	0.5
C	6.6	5.8
S	0.03	0.01
P	0.12	0.08

Experiments with the Tetronics 1.4-MVA plasma furnace were conducted at a power level of about 450 kW (1400 A, 300 V). Approximately 4.5 tonnes of metal were tapped continuously in two runs lasting a total of 8 hours. The energy consumption was 795 kWh/t of metal produced. The losses of manganese in the baghouse represented 0.65% of the manganese fed to the furnace, and about 8% of the feed reported to the slag. As a result of the relatively small scale of the furnace, the thermal efficiency was about 75% compared to an expected value of over 90% for operation on a larger scale, for which energy consumption would approach more closely the theoretical value of 450 kWh/t. The chemical composition of the consumed metal fines and the produced alloys are given in Table 5-5.

Table 5-5 Co-melting of Ferromanganese Fines in the Tetronics 1.4 MVA Plasma Furnace: Chemical Analyses of the Feed and the Product [83]

MATERIAL	Feed (% mass)	Product (% mass)	
	High-carbon Ferromanganese size <6 mm	Run 1	Run 2
Mn	75.5	74.0	76.2
Fe	14.5	17.9	15.8
Si	0.7	0.2	0.1
C	7.0	6.0	6.8
S	<0.01	<0.01	<0.01
P	0.07	0.09	0.09

The MINTEK 100-kVA furnace was also used in co-melting of ferromanganese and silicon fines. In this operation, high-carbon ferromanganese and silicon fines were remelted simultaneously in an attempt to produce a valuable low-carbon silicomanganese from off-grade metal fines. Initially, a heel of mild steel fines, divided into 12 batches, were fed to the furnace. The furnace was tapped after the remelting of each batch of material. The 12 melts consisted of three series of four melts each. The silicon-to-ferromanganese ratio was increased in steps, from 0.18:1 for the first series of four batches to 0.38:1 for the next series and to 0.67:1 for the last series. Different ratios were employed in the three successive groups of runs to yield alloys with variable silicon contents. The composition of the feed materials and the average analyses of each series of melts are given in Table 5-6.

Table 5-6 Co-melting of Ferromanganese and Silicon Fines in the MINTEK 100-kVA Furnace: Chemical Analyses of the Feed and the Products

MATERIAL	Feed (% mass)		Product (% mass)		
	High-carbon Ferromanganese size < 6 mm	Silicon size < 6 mm	Run 1	Run 2	Run 3
Mn	73.8	< 0.1	63.1	60.8	54.6
Fe	13.4	1.3	21.9	13.5	11.8
Si	0.8	93.0	11.3	23.6	32.8
C	6.6	0.2	2.8	0.8	0.1
S	0.014	< 0.01	< 0.01	< 0.01	< 0.01
P	0.008	< 0.01	0.08	0.08	0.07

It can be seen in Table 5-6 that the carbon content decreased substantially relative to that of the ferromanganese feed material; thus, yielding satisfactory alloys. The removal of the carbon took place as soon as the feed became molten.

Refinery experiments were also carried out by MINTEK in the same 100-kVA furnace. In these tests manganese ores of different basicities were reacted with high-carbon ferromanganese, a metal-to-ore ratio of 2:1 was used each time. A wide range of basicities was selected so that the influence of ore basicity on the degree of refining could be studied. During each experiment, about 10 kg of charge material (composed of high-carbon ferromanganese and one of the ores) was fed to the furnace. The average duration of a run was about 1 hour and the arc power was kept around 30 kVA (500 A, 60 V). The bath temperature was varied in a narrow range (1580° to 1620°C). The chemical composition of the feed materials are given in Tables 5-7 and 5-8.

Table 5-7: Refining of Ferromanganese Fines in the MINTEK 100-kVA Furnace: Chemical Analyses of the Metal Feed (percentage mass)

Material	Mn	Fe	Si	C	S	P
High-carbon ferromanganese <6 mm	75.8	13.4	0.83	6.6	0.014	0.08

Table 5-8 Refining of Ferromanganese Fines in the MINTEK 100-kVA Furnace: Chemical Analyses of the Ore Feed (percentage mass)

Ore Number	MnO	FeO	CaO	MgO	Al_2O_3	SiO_2
1	45.0	18.5	5.0	0.8	7.3	19.7
2	42.8	12.9	8.5	2.2	4.5	27.3
3	54.2	13.7	10.7	4.2	0.8	10.8
4	52.1	12.2	17.5	3.6	0.9	8.9
5	50.3	10.5	21.4	6.2	0.7	7.3

In these experiments, South African Mamatwan and Wessels ores were used for preparation of the feed and the feed basicity was regulated by the use of quartz or a mixture of limestone and dolomite during the melting of the ores.

The chemical composition of the manganese ferro-alloys produced are given in Table 5-9, from which it can be seen that both carbon and silicon contents of the metal were reduced. In runs 2 and 3, in which the greatest degree of refining took place, an overall manganese recovery of 86% was obtained. In both instances, the amount of manganese recovered in the refined alloy was about the same as the amount of manganese introduced by the high-carbon ferromangenese fines.

Table 5-9 Refining of Ferromanganese Fines in the MINTEK 100-kVA Furnace: Chemical Analyses of the Metal Produced (percentage mass)

Run No.	Feed		Metal analysis *				
	Ore No. **	Basicity ***	Mn	Si	C	S	F
1	2	0.4	67.5	0.32	5.8	<0.005	0.09
2	3	1.4	70.6	0.16	1.7	<0.005	0.08
3	4	2.4	70.4	0.12	1.8	<0.005	0.08
4	5	3.8	68.8	0.08	3.2	<0.005	0.09

* The balance in iron
** See Table 5-8
*** Basicity = (% CaO + % MgO)/%SiO_2

This experimental investigation has proved that ferro-alloy fines can be remelted and refined in a plasma furnace.

UNITED KINGDOM

Tetronics Research and Development Ltd., England has also tested the melting/remelting of ferromanganese fines using their 3-MVA plasma furnace. The power inputs were up to 696 kW.

Seven tonnes of high carbon ferromanganese fines containing a proportion of slag were remelted during these trial runs [39]. In

the initial part of the trial, the fines were remelted with no additions, whilst in the latter part of the trial 2% of the carbon was added to reduce the MnO content of the slag to improve the manganese recovery to the metal products.

The analysis of the ferromanganese fines used and the average analysis of the metal products are given in Table 5-10. The average analysis of the slag produced are shown in Table 5-11.

Table 5-10 Melting/Remelting of Ferromanganese Fines in the Tetronics 3-MVA Plasma Furnace: Chemical Analyses of the Ferromanganese Fines and the Metal Product (percentage mass)

Material	Mn	Fe	Si	C	S	P
Raw material fines	69.0	15.2	1.5	6.0	0.05	0.09
FeMn	69.0	22.3	0.6	6.0	0.04	0.11
FeMn + 2% C Addition	71.0	19.0	1.0	6.5	0.06	0.10

Table 5-11 Melting/Remelting of Ferromanganese Fines in the Tetronics 3-MVA Plasma Furnace: Chemical Analyses of the Ferromanganese Slags Produced (percentage mass)

Material	SiO_2	CaO	MgO	Al_2O_3	MnO	FeO
FeMn	32.6	16.5	4.3	5.9	38.9	0.6
FeMn + 2% C Addition	35.4	18.8	4.4	11.8	28.9	0.8

It can be seen in Tables 5-10 and 5-11 that remelting the fines had little effect upon the manganese content of the ferromanganese product, however the addition of 2% carbon to the fines increased the product percentage of manganese from 69.0% to 71.0% by reduction of the MnO in the slag phase from 38.9% to 28.9%. On average 10% of the manganese in the raw materials was reported to the slag phase and 3.0% to the exhaust gas and baghouse filter.

This trial has shown that metallic ferro-alloy fines can be directly recycled to the plasma furnace for remelting and production of a bulk ferro-alloy product (ferromanganese in the described case) free from slag and suitable for use in the steel industry. The melting energy approached the predicted values of 410 kWh/t of fines.

U.S.S.R

As already mentioned in Chapter 2, the U.S.S.R. appears to have a leading position in commercial plasma installations for primary melting and remelting installations. The specific information, however, on the performances of these installations is not available.

U.S.A.

The application of thermal plasma to cupolas is under development at the Westinghouse Plasma Center, near Pittsburgh, Pennsylvania.

This experimental program to demonstrate the advantages of the plasma-fired cupola was initiated in October 1983 jointly sponsored by Westinghouse, the Electric Power Research Institute, Modern Equipment Company and General Motors. A

2.5-t/h test cupola melting system, designed and built by Modern Equipment Company, has been installed at the Westinghouse Plasma Center and fitted with a 1.5-MW Westinghouse plasma torch at the tuyere. The operating results of this experimental program are expected to be available by the end of 1985 [13].

In the cupola, molten iron is produced for casting by melting scrap. The cupola has a certain similarity to a blast furnace, but the coke serves only as the source of heat and carbon in the metal (necessary for the mechanical properties of cast-iron). No reduction of ore is involved.

Plasma firing of cupolas would substantially reduce the coke consumption as well as air pollution. The estimated reduction of operating cost is about US$21.66/t (US$72.75/t in a conventional cupola versus US$51.09 in a plasma-fired cupola) [13]. Nevertheless, while plasma melting in cupolas may be attractive in the U.S.A. in relation to large foundries associated with automobile industry, the potential for such a plasma application in Canada appears to be quite limited since here cupolas are numerous but small, most producing less than 10 t/h of molten iron, the largest is 45 t/h of iron [44]. It would be difficult to justify the capital cost for converting these small cupolas for plasma firing.

5.1.1 Plasma Ladle Heating

Plasma heating in ladles to keep the metal in a molten state and temperature adjustment during the ladle refining may be another potential plasma application closely related to plasma melting/remelting. ASEA, Sweden; PEC, U.S.A.; and SINTEF, Norway have been involved in development and demonstration of plasma application in ladles.

ASEA DC ARC LADLE FURNACE

The ASEA DC arc plasma furnace with a central graphite electrode (cathode) and a hearth connection (anode) has been modified specifically for ladle heating application [84]. The DC current flow causes the molten melt and slag to move downwards in the central region of the ladle below the DC arc and upwards along the sidewalls. To reduce the ladle furnace lining wear associated with this rigid flow of the melt, coils have been installed in the ladle furnace. The secondary electromagnetic field induced by the coils changes the melt flow pattern in the ladle furnace to reduce the lining wear.

PEC PLASMA LADLE HEATING

Ladle heating based on application of Plasma Energy Corporation (PEC) water-cooled plasma generators described in Chapter 2 has been demonstrated by PEC jointly with steelmaking company in the U.S.A. [15]. Compared to gas heating, application of these plasma generators should improve the ladle efficiency compared to gas heating, since the ladle may be completely covered. The tests and demonstration of PEC plasma ladle heating is continuing.

SINTEF LADLE HEATING

Conventional electric-arc ladle heating uses the arc above the molten metal. SINTEF (The Norway Institute of Technology) has developed the immersed-arc heater to heat the liquid metal well below the surface thus allowing more efficient energy transfer [85]. The arc is generated between two co-axial electrodes (see Figure 5-1). AC or DC power supply may be used. A non-oxiding gas, e.g., nitrogen is introduced in the annulus between the electrodes. A cavity is formed at the end of the arc heater in which the arc can be sustained.

A 1-MW plasma arc heater for immersed ladle heating was built and installed at the Hella Sweteverk, Norway to heat 8-tonne ladles of 75% ferrosilicon. The electrodes consisted of an outer graphite tube (200 mm OD, 130 mm ID) and a graphite rod (Dia. 80 mm) which could be moved inside the tubular electrode. Typically for this heater, 150 to 250 volts at 2 to 2.5 kA DC are used. When the positive pole was attached to the rod, the arc stability was higher.

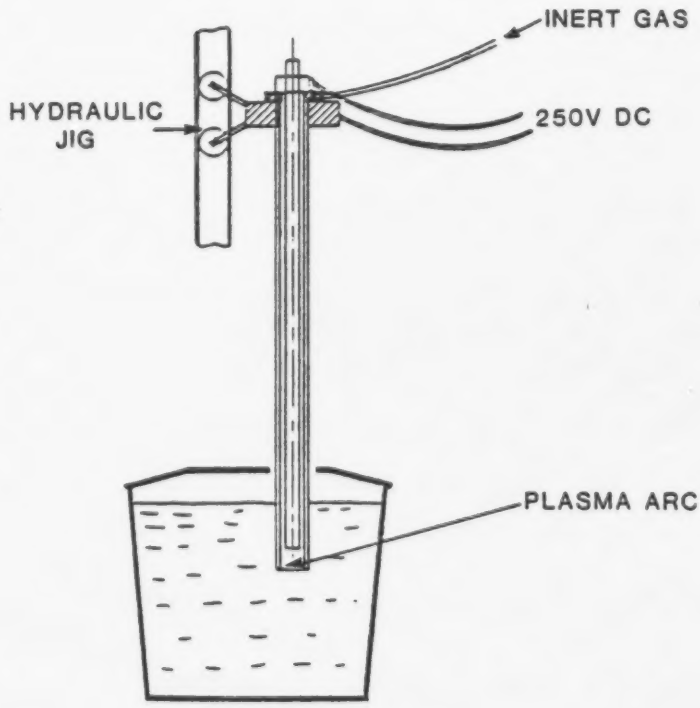


Figure 5-1 The SINTEF Immersed-Arc Heater System

5.1.2 Recovery of High-value Alloy Scrap

Recovery of high-value alloying components by plasma treatment of turnings, scrap or rejects from aerospace industries, gas turbine manufacture, high-resistance bearings and ball bearing production, high performance high temperature compressors, etc., is basically a melting operation, in which the molten anode product can be continuously cast into ingots of controlled composition, ready for re-use. Some refining can be effected, if needed, by the addition of suitable fluxes.

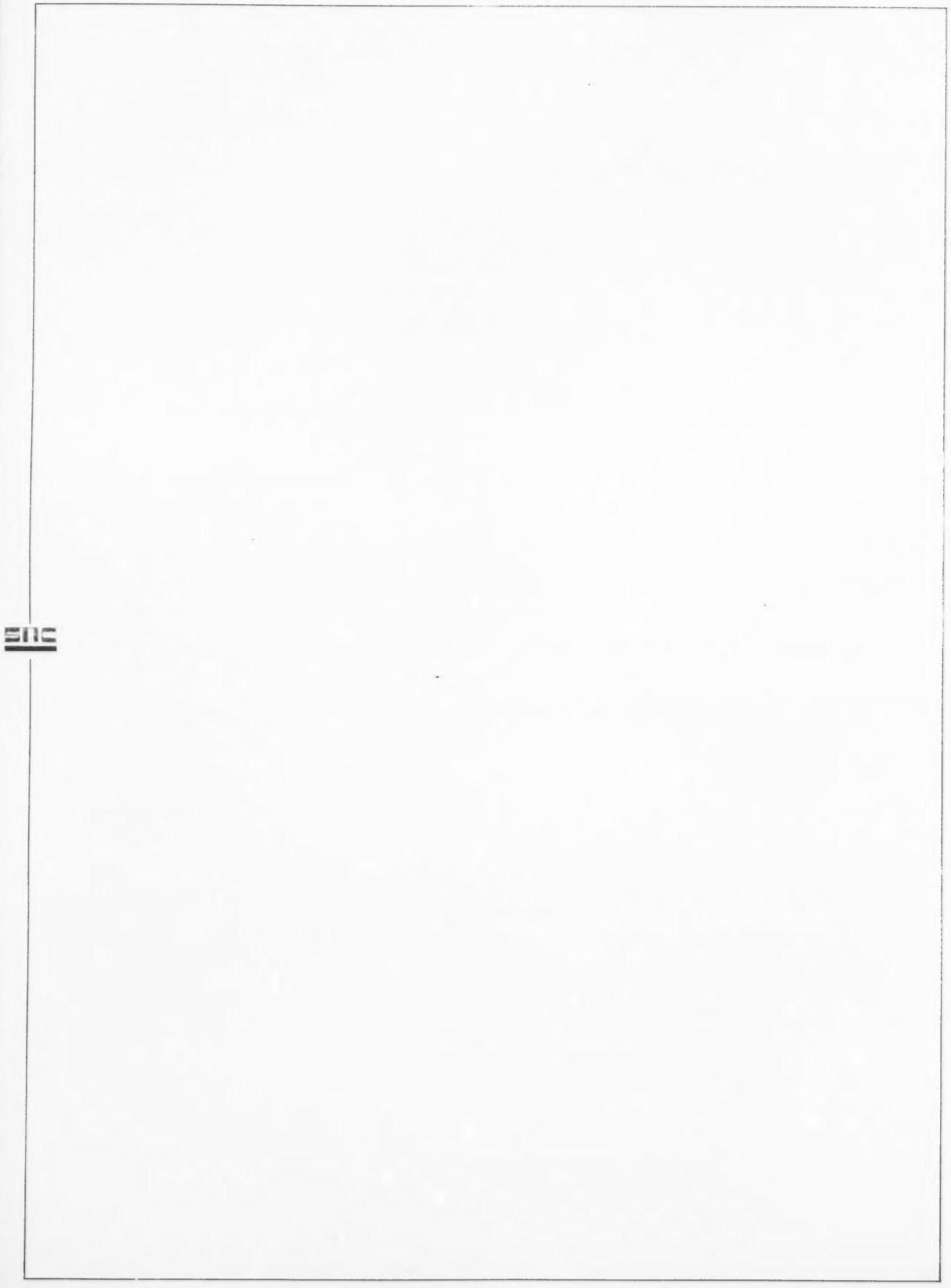
The value of the alloying components such as cobalt, nickel, chromium, titanium, molybdenum, tantalum, beryllium, and yttrium contained in the scrap is quite high. Their recovery is potentially a very lucrative industry.

Plasma treatment of the above-mentioned scrap for the recovery of high-alloy elements could displace the conventional technology used for this purpose. An additional advantage of this plasma application is the elimination of the remaining traces of undesirable volatile impurities (such as antimony, arsenic, bismuth, sodium, potassium, and magnesium) which would be vented off with the effluent plasmagen gas because of their high vapour pressure, as demonstrated by the Noranda Research Centre [33].

The value of these recovered alloys ranges from US$20 to US$40 per kilogram, as demonstrated by United Technologies, U.S.A. [34].

CHAPTER 6

PLASMA APPLICATION FOR HYDROCARBON CONVERSION



6.0 PLASMA APPLICATION FOR HYDROCARBON CONVERSION

The conversion of hydrocarbons at elevated temperature using electric-arc/plasma technology has been the subject of many studies, publications and patents, spanning roughly the period from the early 1920s to the present time. Of all the applications investigated, considerable attention has been given to the production of acetylene as an intermediate product from various hydrocarbon feedstocks such as natural gas, heavy oils and, more recently, coal.

The development of a commercial process for the manufacture of acetylene from hydrocarbons began as early as 1920 when Badische Anilin- und Soda-Fabrik (BASF) initiated a research program, based on Berthelot's laboratory investigation on conversion of low-molecular weight aliphatic hydrocarbons to acetylene by means of thermal cracking [86].

Development of the electric-arc process by BASF led to the first commercial operation at Chemische Werke Hüls AG (F.R.G.) in 1939. The Huels electric-arc reactor has been described earlier in Section 2.2.

The present production capacity of this process, which has been in operation and constant development over the last 45 years, is estimated at 120 000 t/yr of acetylene, 50 000 t/yr ethylene, and 500 million m^3/yr of hydrogen as a by-product. The Huels arc-reactor has operational flexibility in terms of feedstocks such as natural gas, refinery gas, liquefied petroleum gas, or light naphtha. The acetylene produced is mainly used for vinyl chloride monomer, butanediol, and trichloroethylene production.

In the U.S.A., commercial manufacture of acetylene was initiated by Monsanto Chemicals in 1940 at Texas City, producing 50 000 t/yr (110 million lb/yr) of acetylene. In the following years, rapid expansion occurred and several acetylene plants were built worldwide until about mid-1960s, when acetylene was gradually displaced by cheaper petroleum-derived ethylene as a feedstock for petrochemicals products. The worldwide annual capacity of acetylene estimated at 1 110 000 t/yr (2.4 billion lb/yr) in 1965 fell to 800 000 t/yr (1.8 billion lb/yr) in 1976, and to only 300 000 t/yr (660 million lb/yr) in 1983.

E.I. Dupont de Nemours and Company also operated a modified "rotating" electric-arc process at Montagne, Michigan to produce 50 million lb/yr acetylene from natural gas for their chloroprene/neoprene rubber plant [87,88]. The Dupont facility was closed down in 1973 due to poor economics and operating problems.

The oil crisis in the 1970s, resulted in renewed interest in the electric-arc/plasma technology. The driving force behind the development efforts was the acute shortage foreseen and spiralling increase in the price of crude oil and its derived feedstocks.

In 1971, the U.S. Office of Coal Research awarded a contract to AVCO, Massachusetts to develop an electric-arc/hydrogen plasma reactor for conversion of coal to acetylene. Initial tests were made in a 200-kW bench-scale reactor and later in a 1-MW pilot reactor.

In the F.R.G., similar work was initiated later by Chemische Werke Hüls A.G. [89] and Bergbau-Forschung GmbH [90]. Huels developed the arc-coal process in an 80-kW reactor, later tested in a 500-kW pilot reactor and is planning to demonstrate a 8.5-MW prototype unit, scheduled for completion in 1986.

In Canada, a test program to convert Canadian coke to acetylene in a hydrogen/plasma at reduced pressure was sponsored by CANMET. Other researchers centred their efforts on production of synthesis gas from coal, peat, or wood. Techno-economic evaluation made by Noranda [91] for peat to make methanol showed that the proposed process was promising, particularly for the production of chemicals derived from methanol, such as acetic acid, formaldehyde, methyl butyl, ether, etc. Nevertheless, a study by PAPRICAN [92] for fuel gas from wood using plasma has shown that it is not economic even at the low electricity rates in Canada.

A review of various acetylene processes was presented by Miller [89] and Tedeschi [93]. A common principle, however, characterizes all the hydrocarbon-based acetylene processes. Typical hydrocarbon feedstock is subjected to intense energy source, whereby it is heated to between 1200° and 1800°C in a very short time (0.01 to 0.001 second). At 1200°C or higher temperatures, acetylene has lower free energy (i.e., more stable) than any other hydrocarbons, therefore acetylene is the predominant specie formed. But even at these temperatures, acetylene is less stable than its elements (carbon and hydrogen). Therefore, the cracked gas containing acetylene, hydrogen and other elements must be rapidly cooled ($<$10 ms) to 300°C or lower to stabilize the acetylene formed and prevent from decomposition to carbon and hydrogen.

In the electric-arc process, heat is essentially transferred by means of high temperature electric-arc. In the conventional process, namely the Wulff, heat is transferred in a regenerative furnace. Others such as the one-stage and two-stage partial oxidation processes (BASF, Sachsse, Union Carbide, Montecatini) involve partial combustion of the feedstock to provide the necessary heat to attain the reaction temperatures ($>$1200°C).

To evaluate the potential of electric-arc/plasma technology in Canada for hydrocarbon conversion, the following cases were examined:

Reactor/Configuration	Feedstock	Product	Plant Capacity	Plant Location
1. a) Electric-Arc Reactor (Chemische Werke Hüls, F.R.G.) b) Preheated or Hydrogen Plasma (Westinghouse, U.S.A.) c) Resistance-Heated (Happel and Kramer, U.S.A. and SINTEF, Norway)	Natural Gas	Liquid Fuel	12 500 bbl/d gasoline	Québec
2. Electric-Arc Reactor (Chemische Werke Hüls, F.R.G.)	Natural Gas	Acetylene	50 and 300 Mln lb/yr acetylene	Alberta and Québec
3. Arc-Coal Reactor (AVCO, U.S.A.)	Canadian sub-bituminous Forestburg coal	Acetylene	50 and 300 Mln lb/yr acetylene	Alberta

The preliminary conceptual plant designs corresponding to the above cases have been developed for the screening-type evaluation based on the data supplied by various process developers. Data received were verified for consistency and accuracy. Where operating conditions were not specified by process developers, they were chosen by SNC based on the available information and criteria established.

6.1 LIQUID FUEL PRODUCTION FROM NATURAL GAS VIA ACETYLENE

In this section, the overall conceptual plant design of a commercial liquid fuel plant (12 500 bbl/d gasoline product) via plasma conversion of natural gas to acetylene is presented, using three alternative plasma reactor configurations: Huels reactor (natural gas used as plasmagen), Westinghouse reactor with hydrogen as plasmagen gas, and the resistance-heated-type reactor. The overall configuration includes the acetylene plant, catalytic hydrogenation, olefin oligomerization and hydrogen recovery units along with the required support systems, utility and offsite facilities to comprise an essentially integrated, self-sufficient operation.

The preliminary techno-economic evaluation presented below is based on the cost-shared study (Contract No. OSQ83-000070, DSS File No. 26SQ.23440-3-9076) carried out by SNC for Energy, Mines and Resources Canada, CANMET [94]. The techno-economic data expressed in mid-1984 in the above study have been updated to March 1985 Canadian dollars using the Construction Price Indexes published by Statistics Canada (Catalogue No. 62-007, March 1985).

Natural gas, LPG and electricity are the basic raw material and process input, LPG being used as a quench to stabilize the intermediate acetylene and also to recover part of the process heat. Make-up water, catalysts and other chemicals are also needed but in relatively smaller quantities. During steady-state operation, steam is generated by recovering process heat and burning fuel gas, residual oil and the carbon formed in the acetylene reactor. Excess fuel gas is used to generate part of the electricity, the balance is purchased from an external source.

Overall material and energy balance, product efficiencies and a utility summary are also given for each process.

6.1.1 Huels Electric-Arc Acetylene Process

The overall block diagram showing the interrelationship between the various processing areas for an integrated liquid fuel plant is shown in Figure 6-1. The main processing areas may be subdivided as:

- Acetylene reactor/quenching
- Gas purification and primary product separation
- Acetylene hydrogenation
- Mobil Olefin to Gasoline and Diesel (MOGD) process, and
- Hydrogen recovery (Pressure Swing Adsorption, PSA)

6.1.1.1 Acetylene Reactor and Quenching

The Huels electric-arc reactor was described earlier in Chapter 2. For the proposed plant capacity, 55 reactors each of 9-MW rating are required.

Typically, the feed gas passes through the arc at about 1000 m/s and the residence time is in the order of 2 ms. Overall conversion of methane is between 70 and 75 wt%.

The hot gases leaving the arc zone and containing mainly acetylene, hydrogen, higher acetylenes, dienes, unreacted methane and some carbon monoxide have substantial energy because of high temperature (about 1500°C). About 20 cm below the anode, cold propane/butane is introduced into the reactor through several nozzles D (see Figure 2-13) to cool the gas stream to between 800° and 1000°C and to stabilize the acetylene formed. The

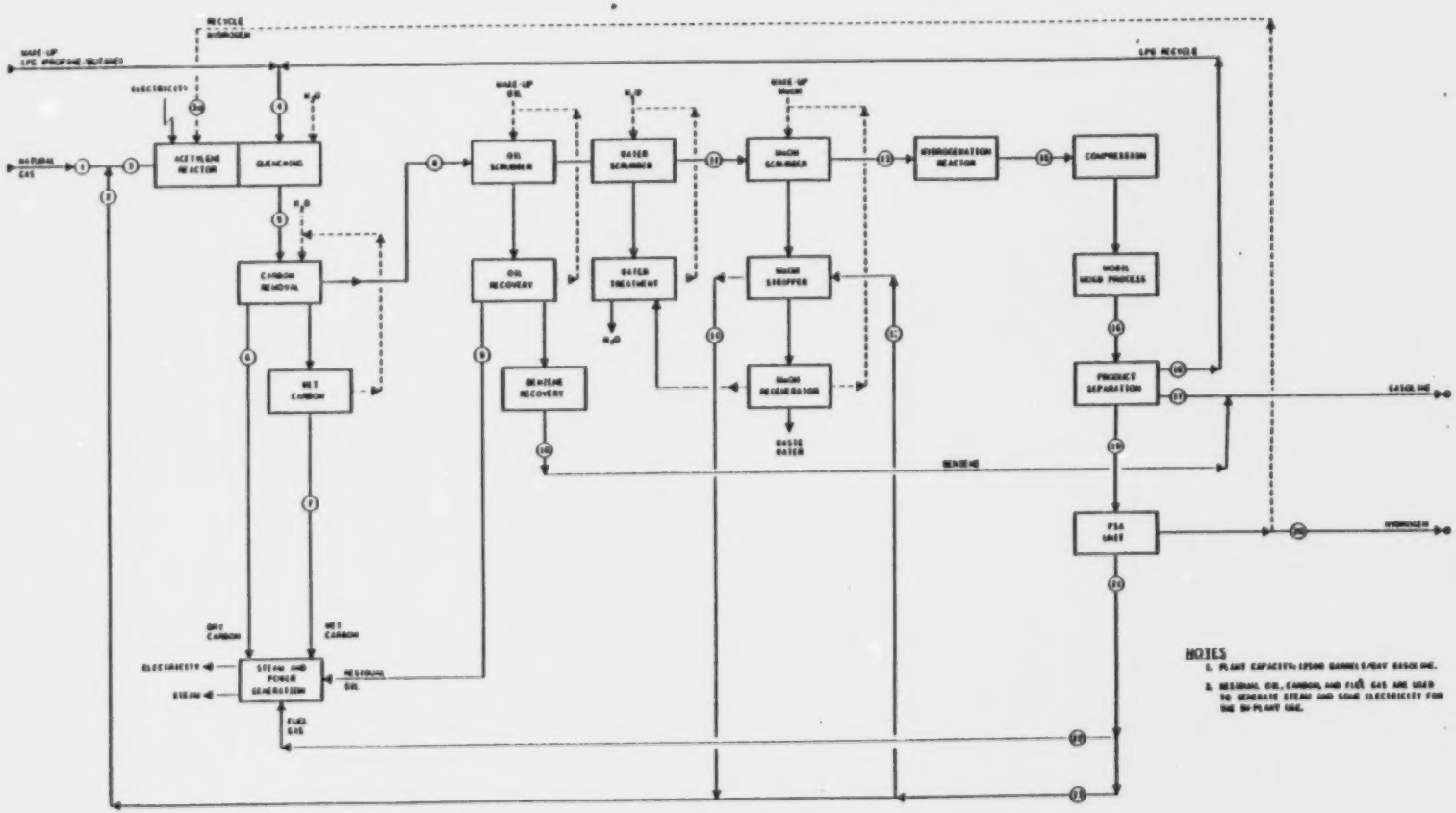


Figure 6-1 Overall Configuration of a Liquid Fuel Plant Via Acetylene

cold LPG quench is mainly converted to ethylene. The exiting hot reaction mixture is further cooled to between 200° and 250°C by means of a water spray. The residence time during quenching is less than 2 ms.

The reactor's specific energy requirement is about 11.3 kWh/kg of acetylene formed.

On a carbon-free basis, acetylene concentration in the product gas stream is about 15%. The exiting gas stream undergoes a series of gas processing and product separation steps as described below:

6.1.1.2 Gas Purification and Primary Product Separation

As shown in Figure 6-1, most of the carbon black is initially removed from the product gas stream as dry carbon (3 to 4 wt% H_2O, 5 wt% hydrocarbons) by a series of cyclone separators. The balance is rejected as wet carbon (50 wt% H_2O, 25 wt% hydrocarbons) in a water spray tower. The wet carbon black is then sent to the horizontal filters to reject excess water. Both dry carbon and wet carbon filter cake is used as a fuel to generate steam for the process.

The solids-free gas (containing less than 3 mg carbon/m^3 of gas) is treated in an oil venturi and scrubber to remove naphthalenes and other hydrocarbons. Benzene is further recovered as a by-product by distillation and blended with gasoline. The gas stream is then treated in a water scrubber to remove traces of hydrocyanic acid.

The effluent gas is compressed to 1.5 MPa in four-stage reciprocating compressors and then treated in methanol scrubbers operating at 30°C to separate C_3/C_4 dienes and higher acetylenes before being recycled to the reactor.

The remaining gas stream is heated to about 150°C before feeding into the catalytic hydrogenation unit.

6.1.1.3 Acetylene Hydrogenation

Selective hydrogenation of acetylene to ethylene is carried out "in-situ" over Pd base catalyst at 150° to 175°C and 1.4 MPa using hydrogen present in the gas stream. Other typical catalysts include platinum, nickel and cobalt [95].

Conversion of acetylene to ethylene is high ($>$ 90%) and the reaction is highly exothermic (175 kJ/gm-mole). Other side reactions which also take place are conversion of olefins such as ethylene, propylene, and butylene to saturated hydrocarbons. Excess heat is used to preheat the exiting olefin-rich stream to 150°C and to generate steam for the process.

The olefin-rich stream (52 wt% ethylene, 4 wt% propylene and 1.4 wt% butenes) is compressed to 3.45 MPa (500 psi) and preheated to 315°C (600°F) before to feeding into the MOGD reactor.

6.1.1.4 Mobil Olefin to Gasoline and Distillates (MOGD) Process

MOGD is a catalytic process developed by Mobil Research and Development Corporation for converting light olefinic compounds to high quality gasoline and/or distillates. The process is based on the Mobil synthetic zeolite catalyst (ZSM-5) which

selectively oligomerizes the light olefins to the desired product. Though normally designed to process propylene and butylene, MOGD is applicable to a wide range of feedstreams ranging from ethylene to olefinic naphtha [96].

6.1.1.5 Hydrogen Recovery Using Pressure Swing Adsorption (PSA) Unit

The offgas leaving from MOGD process at 40°C is compressed from 1.24 MPa (180 psi) to 2.4 MPa (350 psi) and fed into the Union Carbide Polybed Pressured Swing Adsorption unit. Essentially, the PSA unit is based on the principle of pressure reduction to remove adsorbed components from the molecular sieve (adsorbent) which adsorbs nearly all the components other than hydrogen from the inlet gas stream.

6.1.1.6 Overall Material and Energy Balance

SNC

The overall material and energy balance is summarized in Table 6-1.

The main product is gasoline. Hydrogen is the by-product. Residual oil, carbon black and excess fuel gas are used to generate steam and 95 MW of electricity within the plant. All low-pressure steam required for the process (32 675 kg/h) is generated by recovering process heat from the acetylene hydrogenation unit. The excess low-pressure steam (62 240 - 32 675 = 29 565 kg/h) is used for generating high-pressure steam.

The make-up water requirement is 910 m^3/h, or about 4000 US gpm. The large volume of this make-up water is mainly due to losses and consumption of water in water-coolers.

Table 6-1 Overall Material and Energy Balance Summary
(Huels Electric-Arc Acetylene Process)
[Plant Capacity: 12 500 bbl/d Gasoline Product from Natural Gas]

	Flow rate/Quantity	Unit Basis** per kg of gasoline
Process Input		
Natural Gas	81 170 kg/h	1.30 kg
LPG	14 225	0.23
Scrubbing Oil	930	-
Methanol	465	-
Electricity		
Acetylene Reactor	532 MW	8.5 kWh
*Plant Use	95	1.5
	627	10.0
Products/By-products		
Gasoline (12 500 bbl/d)	62 339 kg/h	-
Hydrogen	10 816	0.17 kg
*Residual oil	4 030	0.065
*Carbon black (dry)	11 245	0.18
(wet)	5 623	0.09
*Fuel Gas (110 GJ/h)	3 630	1.76 MJ

* Residual oil, carbon black and fuel gas are used to generate steam and some electricity for in-plant use.

** 1 kg = 1.3342 L (gasoline).

The "overall product" efficiency is 60.3%. It is calculated as the total heating value of all products (gasoline and hydrogen) divided by the input energy of natural gas, LPG and electricity. Similarly, the desired gasoline product efficiency is 41.8%.

6.1.1.7 Commercialization Status

The electric-arc reactor configuration of Chemische Werke Hüls has been extensively tested and commercially proven for over 45 years.

6.1.2 Liquid Fuel from Natural Gas with Hydrogen-Plasma Acetylene Reactor

The overall processing scheme is similar to that described earlier for the electric-arc reactor except that:

- the hydrogen plasma reactor is used for acetylene production;
- a portion of recovered hydrogen is recycled to the acetylene reactor to preheat the feed.

Differences in the operating conditions and product yields are described below. Design features of the hydrogen plasma reactor system are also presented.

6.1.2.1 Hydrogen Plasma Acetylene Reactor

The use of hydrogen as an auxiliary gas for heating and pyrolysis of natural gas is particularly attractive as it acts as a suppressant for carbon formation by reducing acetylene decomposition [97]. Also, hydrogen is formed as a by-product

with the acetylene, therefore use of hydrogen does not complicate the product separation and recovery procedure.

The reaction $H_2 \longrightarrow 2H$ in the arc zone is highly endothermic (ΔH = 429 kJ/gm-mole). At the plasma temperature of 5000°C, the concentration of hydrogen ions is almost 99%, dropping to 1% at 2500°C. Therefore, on cooling from the plasma state to acetylene reaction temperature ($\simeq$ 1500°C), it provides 565 kJ/mol. Also, heat content of hydrogen gas leaving the arc zone at 1200°C is only 5% of its enthalpy at 5000°C, thus the penalty for heat loss is low.

The hydrogen-plasma reactor is of the type used by Westinghouse [98] for production of acetylene from hydrocarbons including natural gas, from coal by AVCO [99] and by Chemische Werke Hüls [100].

For the 12 500 bbl/d liquid fuel plant, about 70 plasma torches are required. As shown in Figure 6-1, natural gas mixed with recycle stream is fed into the hydrogen plasma reactor. The hot product gas is quenched with cold LPG and water as in the case of the electric-arc reactor described earlier.

The reactor specific energy requirements [SER] is about 14.5 kWh/kg of acetylene formed. On a carbon-free basis, the acetylene composition is about 12.3 mol %. The lower concentration is primarily due to some dilution of the product gas stream by preheated hydrogen.

The reactor effluent undergoes a similar gas processing and product separation steps as described earlier in Sections 6.1.1.2 to 6.1.1.5.

6.1.2.2 Overall Material and Energy Balance

The overall material and energy balance is given in Table 6-2.

All the low-pressure steam required for the process is generated by recovering process heat. Excess low-pressure steam is used for generating high pressure steam.

The make-up water requirement is about 705 m^3/h or about 3100 US gpm.

6.1.2.3 Commercialization Status

Westinghouse has developed the plasma generators (torches) for various applications ranging from iron-making, ferro-alloy production and chemical processing. Several DC torches of different power ratings ranges from 75 kW unit (MARC 3), 2 MW (MARC 11), 3 MW (MARC 31) are being offered. The large prototype unit of 10 MW (MARC 100) is under development (see details in Chapter 2).

For acetylene production, however, tests to date have been made up to 3 MW only. Demonstration of the prototype unit will be required to establish the feasibility of the reactor for commercialization.

6.1.3 **Liquid Fuel from Natural Gas with Resistance-Type Acetylene Reactor**

Once again, the overall processing scheme is similar to that presented in Figure 6-1. The resistance-type reactor is not an

Table 6-2 Overall Material and Energy Balance Summary
(Hydrogen-Plasma Acetylene Reactor Process)

[Plant Capacity: 12 500 bbl/d Gasoline Product from Natural Gas]

	Flow rate/Quantity	Unit Basis** per kg of gasoline
Process Input		
Natural Gas	74 403 kg/h	1.19 kg
LPG	12 612	0.20
Scrubbing Oil	948	-
Methanol	472	-
Electricity		
Acetylene Reactor	690 MW	11.1 kWh
*Plant Use	90	1.4
	780	12.5
Products/By-products		
Gasoline (12 500 bbl/d)	62 386 kg/h	-
Hydrogen	7 850	0.13 kg
*Residual Oil	3 933	0.063
*Carbon black (dry)	4 936	0.079
(wet)	2 843	0.045
*Fuel Gas (315 GJ/h)	5 510	5.0 MJ

* Residual oil, carbon black and fuel gas are used to generate steam and some electricity for in-plant use.

** 1 kg = 1.3342L (gasoline).

electric-arc/plasma reactor. It may be classified as an electricity-based reactor. The design features and description of the resistance-type acetylene reactor configuration are given below.

6.1.3.1 Resistance-Type Acetylene Reactor Configuration

The resistance-type acetylene reactor consists of a system of vertically mounted cylindrical tubes which are progressively larger in diameter, all contained within an outermost metal tube.

Figure 6-2 is a simplified cross-sectional and axial sketch of the resistance-type bench-scale reactor proposed by Happel and Kramer [101]. The narrow annulus space (1 cm O.D, 0.5 cm I.D., and 12 cm length) serves as a reaction zone. A graphite resistor (type ATJ, National Carbon Co.) was used as a heating element. The radiation shield is used to minimize heat losses. The outer shell of the reactor including the 1-cm-thick side plate is constructed of copper. All the outer walls are water-cooled.

The advantage of the "isothermal" resistance-type reactor (which is essentially an isothermal-wall electricity-based reactor) over the electric-arc/plasma processes is that the electrically heated reaction tube is easier to control and to maintain at a uniform temperature profile, thus making it possible to obtain higher yields of acetylene. An experimental study by Happel and Kramer [102] showed that methane conversion up to 95% with acetylene yield up to 90% is achievable. The desired operating condition is reaction temperatures in the range of 1600° to 1800°C with residence time of less than 3 ms and pressures between 30 and 60 kPa.

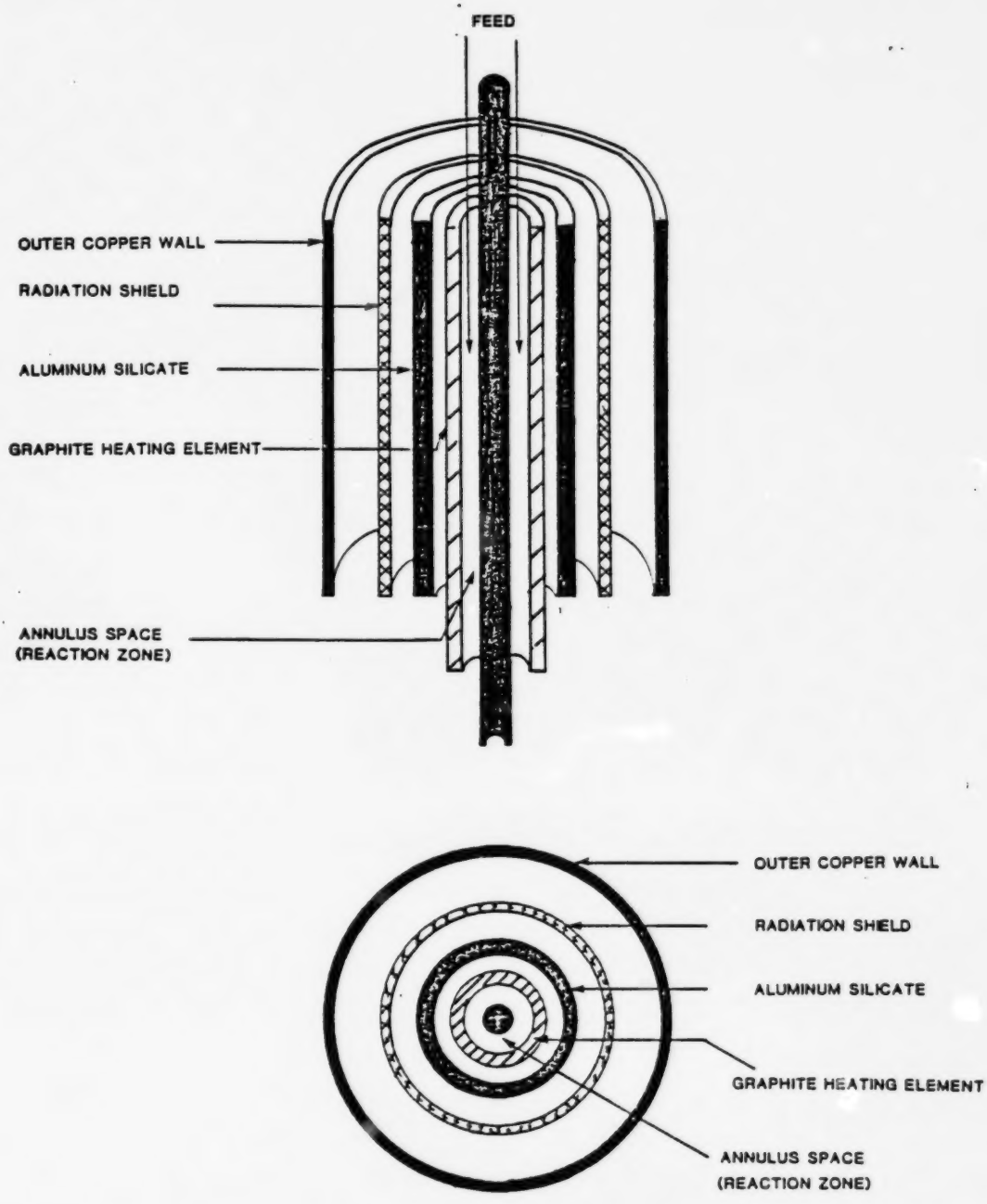


Figure 6-2: Schematics of Resistance-Heated Reactor

Further study was done with a similar multi-tubular reactor having a capacity 50 times higher built and operated by SINTEF [103], although several modifications were made [104]. The reactor tube (CGW graphite from Union Carbide) used as a heating element was 60 cm long having 2-cm outer diameter. Two different inside diameters: 0.7 cm and 1 cm, were tested. A protective lining of aluminum was used*. Undesirable carbon deposits were removed periodically by controlled air combustion. The input power was 1 MW.

For this evaluation, the multi-tubular resistance reactor of 1-m length and a 10-MW power rating was considered. For production of 12 500 bbl/d gasoline, about 55 such reactors are required. The selected operating conditions are reaction temperature of 1750°to 1775°C, residence time of 2 ms and pressure of 50 kPa. These are based on the analysis of bench-scale and pilot-plant data supplied by the process developer and chosen not only to maximize methane conversion and acetylene yield but also to minimize the reactor SER (kWh/kg of acetylene produced).

A conservative value of 88% for methane conversion was assumed. Acetylene yield of 80% was taken. Product yield and distribution data reported for methane only was extended for other components present in the natural gas feed stream. Also, adjustments were made for LPG quench, since in the experimental runs, cold product gas was used as a quenchant.

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* Different materials of construction (e.g., SiC, Mo) were considered in addition to two types of reactor configuration (rod and tubular). The tubular reactor with carbon as a heating element and alumina lining was found to be more flexible and reliable.

The product recovery and separation scheme is similar to that presented earlier for the Huels electric-arc reactor configuration.

6.1.3.2 Overall Material and Energy Balance

A summary of overall material and energy balance is given in Table 6-3.

The make-up water requirement is 815 m^3/h or about 4740 US gpm.

The "overall product" efficiency is 61.7%. Similarly, the desired gasoline product efficiency is 43.6%.

6.1.3.3 Commercialization Status

Comparing various reactor configurations, the so-called "isothermal" resistance-type reactor has the obvious advantage of easier temperature control and more uniform temperature profile in the reactor, thus making it possible to obtain high yields of acetylene and a higher conversion of natural gas. Also, the electrical energy is converted into thermal energy without the complex and relatively expensive rectification, needed in the arc-plasma reactors.

On the other hand, for continuous commercial-scale application, no satisfactory resistor is known.

The resistance-type reactor has so far been tested only on the bench-scale and pilot-plant levels. Further process development using this reactor configuration has been abandoned due to financial constraints [105]. Therefore, the commercial potential of this reactor in the near future is low.

Table 6-3 Overall Material and Energy Balance Summary
(Resistance-Type Acetylene Reactor Process)

[Plant Capacity: 12 500 bbl/d Gasoline Product from Natural Gas]

	Flow rate/Quantity	Unit Basis** per kg of gasoline
Process Input		
Natural Gas	73 042 kg/h	1.17 kg
LPG	15 285	0.25
Scrubbing Oil	820	-
Methanol	420	-
Electricity		
Acetylene Reactor	548 MW	8.8 kWh
*Plant Use	86	1.4
	634	10.2
Products/By-products		
Gasoline (12 500 bbl/d)	62 139 kg/h	-
Hydrogen	10 034	0.16 kg
*Residual Oil	1 090	0.018
*Carbon black (dry)	6 717	0.11
(wet)	3 870	0.06
*Fuel Gas (305 GJ/h)	7 020	5.0 MJ

* Residual oil, carbon black and fuel gas are used to generate steam and some electricity for in-plant use.

** 1 kg = 1.3342 L (gasoline).

6.1.4 Capital, Operating and Product Costs for Plasma Conversion of Natural Gas to Gasoline

6.1.4.1 Capital Cost Estimate and Total Investment

The capital cost estimates for 12 500 bbl/d liquid fuel plant for each of the three alternative reactor configurations are presented in Table 6-4. The plant capital cost estimates and total investments are calculated following the criteria and methodology described in the Appendix and data supplied by the reactor and process developers.

Although the study is not site specific, land costs have been considered for a plot about 40 hectares (100 acres) at an average rate of $27 750/hectare ($2.75/m^2).

Interest during construction is not added to the plant investment, since for calculation purposes it was assumed that the capital required for the project will be provided through 100% equity financing.

Total capital investment is nearly the same (within the accuracy of the cost estimate) for all three reactor configurations. The plasma route, however, for production of gasoline via acetylene is less capital intensive as compared with other synfuel technologies, e.g., the Fischer-Tropsch process or direct coal liquefaction route. Comparisons with these coal liquefaction processes show that the investment required using plasma is less than 50%, as shown below:

	Plasma Route	Coal Liquefaction [106, 107]
Investment, $/daily litre of product	265 - 290	500 - 800

6.1.4.2 Operating, Maintenance and Production Costs

These costs are reported on an annual basis assuming plant operation of 8000 hours a year, i.e., a service factor of 0.91. (See Table 6-4).

Raw material, utilities catalysts and chemical costs have been calculated using unit cost data given in the Appendix and the estimated requirement presented earlier in Tables 6-1, 6-2 and 6-3. Make-up water is purchased at a cost of $\$0.132/m^3$ ($0.50/1000 US gallons).

Running royalties have been estimated using information supplied by process developers and licensors. Operating and supervisory labor costs are calculated using typical labor rates based on manpower requirements specified by the respective process developers.

SNC

To obtain net operating costs, by-product credits have been taken for hydrogen at two values: i.e., at chemical value at $7.58/GJ ($8.00/10^6 Btu) and at fuel value $4.70/GJ ($5/10^6 Btu).

The unit product cost (or transfer price) of gasoline product for each of the three cases considered is also shown in Table 6-4. The net product cost ranges from 43 to 50 ¢/L (at $7.58 by-product value of hydrogen), being nearly the same for the electric-arc and resistance-heated reactor configurations.

Compared with the existing production cost of gasoline (35 to 38¢/L, Dec 1985) from crude oil using conventional technology, the estimated cost of gasoline via acetylene is certainly high, particularly in view of falling prices of crude oil today. The liquid fuel production via acetylene route offers, however, an

Table 6-4 Capital, Operating and Product Cost Estimates for Gasoline Production from Natural Gas (Plant Located in Québec)

[Plant Capacity: 12 500 bbl/d gasoline]

	Millions of Canadian Dollars (March 1985)		
Acetylene Reactor Configuration	Huels Electric-Arc Reactor	Preheated or Hydrogen Plasma Reactor	Resistance-Type Acetylene Reactor
Direct Capital Investment			
Installed Plant Cost (TPC)	484.21	499.10	451.05
Project/Estimation Contingency	48.42	49.90	45.10
Total Installed Plant Cost (TIPC)	532.63	549.00	496.15
Indirect Capital Investment			
Licence and Prepaid Royalties	1.37	1.50	1.50
Initial Catalysts & Chemicals	1.35	1.35	1.31
Start-Up and Other Costs	15.98	16.47	14.88
Sub-Total	551.33	568.32	513.84
Working Capital*	15.98	16.47	14.88
Land*	1.11	1.11	1.11
Total Capital Investment (TCI)	568.42	585.90	529.83
Annual Operating, Maintenance and Production Costs (at $7.85/GJ for hydrogen by-product credits)			
Raw Material and Process Input	248.83	254.42	241.07
Operating Cost	40.11	40.70	38.66
Overheads	19.19	19.76	17.96
	308.13	319.88	297.69
By-products Credits	(77.89)	(56.53)	(72.26)
	230.24	263.35	225.43
Depreciation	27.57	28.42	25.69
Capital Recovery Cost	35.84	40.30	33.90
	293.65	332.07	285.02
Product Cost, ¢/litre			
at $7.85/GJ H_2 by-product credits	44.3	50.1	43.0
at $4.74/GJ H_2 by-product credits	48.7	53.3	47.1

* non-depreciable items

attractive synfuel approach since it involves utilization of two local energy resources, surplus natural gas and electricity.

For Eastern Canada, particularly Québec, the proposed route offers a significant savings in crude oil impact. A 12 500 bbl/d gasoline product represents about 18 000 bbl/d of crude oil equivalent, or about 6 million bbl/yr of crude oil.

6.2 HYDROCARBON AND CHEMICAL PRODUCTION FROM NATURAL GAS VIA ACETYLENE

For many years, acetylene has been used as a major building block for the production of large-volume commodity chemicals as well as lower-volume Reppe acetylene-based products and specialty acetylenic alcohols, diols and other derivatives. In the early 1960s the use of acetylene for the production of commodity chemicals (acrylonitrile, acrylates, chlorinated solvents, chloroprene, vinyl acetate, vinyl chloride) reached a peak of about 454,000 t (1 billion lb) of acetylene [108]. Since then, acetylene has been largely displaced by olefins such as ethylene, propylene, and butadiene derived from cheap cracking feedstocks. These olefins, though less suitable as feedstocks than acetylene for some applications, were still used as they became readily available at prices considerably lower than that of acetylene. Ethylene is the main competitor of acetylene.

On the other hand, the use of acetylene for industrial purposes such as welding, metal cutting and fabrication has remained constant. Nevertheless, there has been a significant growth in Reppe-type chemicals such as butyndiol, butanediol, tetrahydrofuran (THF), n-methyl-2-pyrrolidone, vinylpyrrolidone, and polyvinyl pyrrolidone, besides a variety of smaller volume acetylenic alcohols and glycols and their derivatives.

Within the scope of this study, the feasibility of hydrocarbon production was investigated for acetylene production as a feedstock for:

- Reppe-type chemicals, 22 700 t/yr (50 million lb/yr) acetylene
- Commodity chemicals, 136 200 t/yr (300 million lb/yr) acetylene

Acetylene can be converted to a variety of chemicals, the choice of final end-product for Canada would be dictated by market requirement and analysis, which is beyond the scope of this study. Therefore, capital and operating costs are developed for acetylene production* under the assumption that:

- if the acetylene cost is lower than the present cost of ethylene, then acetylene could potentially substitute ethylene for large-volume commodity as well as low-volume specialty Reppe-type chemicals.

- if the acetylene cost from the electric-arc route is higher than ethylene prices but is lower than the cost of acetylene derived from other routes (e.g., Calcium Carbide, or partial oxidation route), then acetylene produced in the electric-arc process would be attractive for low-volume Reppe-type chemicals.

Also, cost calculations have been developed using Huels electric-arc acetylene technology, since the process is commercially proven and the final product is nearly the same for any of the reactor configurations considered (see Section 6.1.4).

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* It must be noted that acetylene cannot be transported over long distances (except in special cylinders); therefore, the acetylene plant would have to be located adjacent to or near the chemical facility.

6.2.1 Overall Plant Configuration for Plasma Acetylene Production

A simplified flow diagram for acetylene production using electric-arc processing (Chemische Werke Hüls) is given in Figure 6-3. The processing scheme consists of acetylene reactor system, carbon separation and recovery unit, and a series of scrubbers to remove impurities and higher acetylenes as described earlier in Section 6.1.1.1 (Acetylene Reactor and Quenching) and Section 6.1.1.2 (Gas Purification and Primary Product Separation).

The product gas leaving the methanol scrubber undergoes further processing steps as follows:

- Separation of hydrocarbons and higher olefins (C_3^-) using an octane scrubbing unit. Propane and butane are recovered in the subsequent low-temperature fractionation units as by-products, the remaining hydrocarbon-containing gas is recycled to the acetylene reactor.

- Recovery and separation of acetylene (99% pure) in the methanol/n-methylpyrrolidone scrubbing unit.

- Separation of the residual gas into hydrogen, ethylene, methane and fuel gas streams. Hydrogen and ethylene are recovered as by-products. Methane is recycled to the acetylene-arc reactor. Fuel gas is used for steam and power generation.

The overall material balance summary for the two plant capacities (300 and 50 million lb/yr acetylene) is given in Table 6-5. The overall, desired products (acetylene and ethylene) and specific product (acetylene) efficiencies have been calculated as 69%, 41% and 29.3% respectively.

Table 6-5 Overall Material and Energy Balance Summary for Acetylene Production from Natural Gas (Huels Electric-Arc Process)

Plant Capacity t/yr (million lb/yr)	22686 (50)	136116 (300)
Raw Material and Process Input, kg/h		
Natural Gas	4 616	27 695
LPG	2 050	12 297
Scrubbing Oil	210	425
Methanol	210	425
Octane	105	212
Electricity, MW		
Arc Furnace	32	194
Plant Use	5	29
	37	223
Products/By-products, kg/h		
Acetylene	2 836	17 014
Ethylene	1 118	6 706
Hydrogen	1 014	6 086
Propene/Butene	210	1 263
Benzene	125	748
* Residual Oil	244	1 463
* Carbon Black	1 021	6 125
* Fuel Gas	243	1 456
Thermal Efficiency, %		
Overall Product	69.0	69.0
Desired Product (C_2H_2 + C_2H_4)	40.9	40.9
Specific Product (C_2H_2)	29.3	29.3

* Residual oil, carbon black and fuel gas are used to generate steam and some electricity for in-plant use.

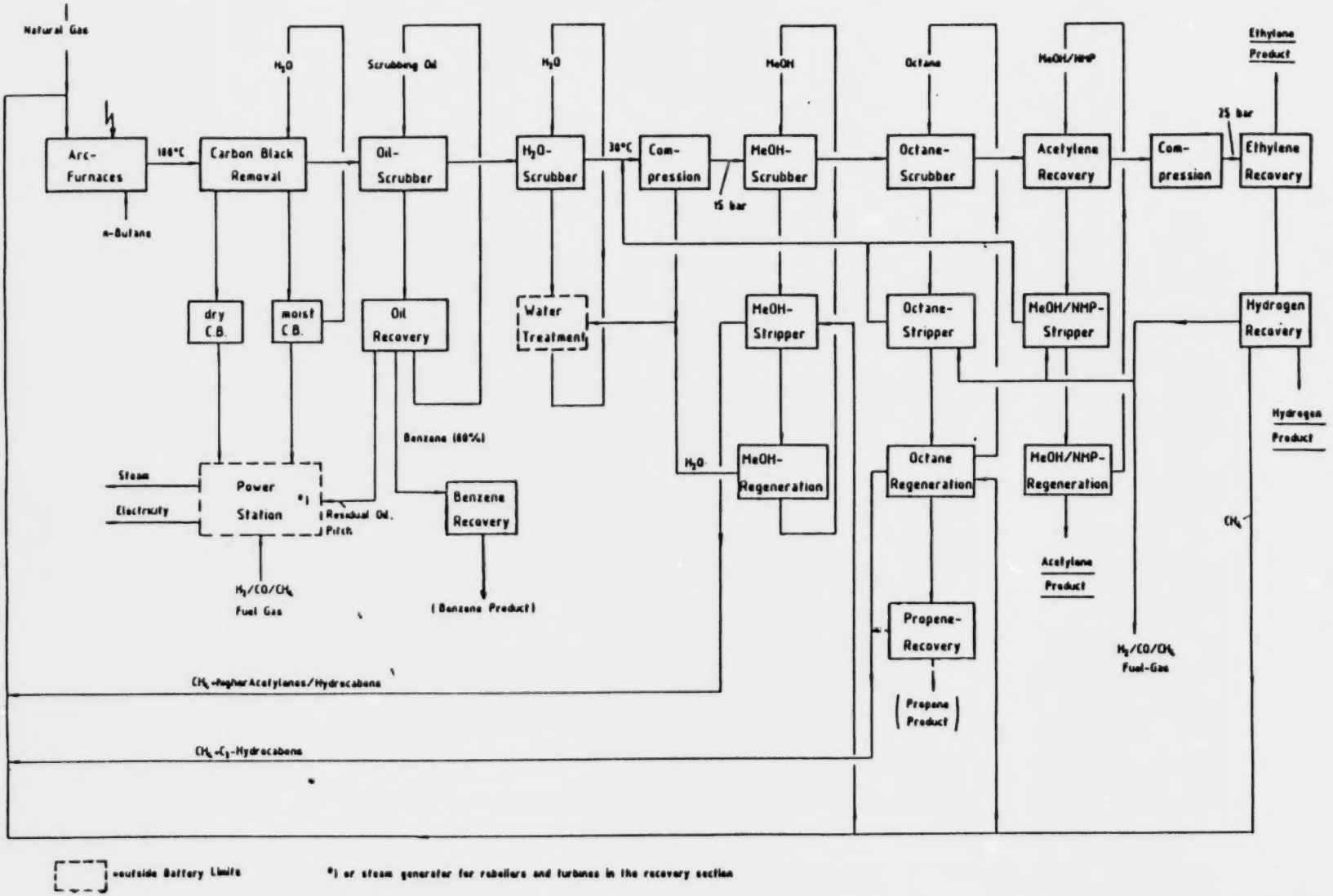

Figure 6-3 Simplified Flow Diagram for Acetylene Production Using the Electric-Arc Process (Chemische Werke Hüls)

6.2.2 Capital, Operating and Production Cost for Acetylene from Natural Gas

Preliminary capital, operating and product cost estimates are summarized in Table 6-6 for two plant-capacities at two locations (Québec and Alberta). These estimates are based on the techno-economic data supplied by Chemische Werke Hüls [109] for the plant units within the plant battery limits and those developed by SNC for the associated offsite facilities. Similar techno-economic criteria and procedures described earlier for the liquid fuel production (see Section 6-1) have been applied for the acetylene plant. Different unit prices and by-product credits, however, have been allowed for Québec and Alberta locations, as shown in the Appendix.

For a 50-million lb/yr plant, the acetylene product cost is about 54¢/lb compared to 70 to 80¢/lb from other routes (i.e., calcium carbide, partial oxidation route for acetylene). The cost differential for acetylene derived from the electric-arc route makes it attractive for production of low-volume specialty Reppe-type chemicals.

For a 300-million lb/yr plant, the acetylene product cost is about 38¢/lb, which is significantly lower than for a 50-million lb/yr plant due to economy of scale. Nevertheless, for commodity chemical production, acetylene must compete with ethylene which is available today at a price of 19 to 20¢/lb. Despite the fact that acetylene would dictate about 5¢/lb premium over ethylene due to its favourable feedstock characteristics, the economics do not appear attractive at this time for large volume chemical production.

Table 6-6 Capital, Operating and Product Cost Estimates for Acetylene Production from Natural Gas (Huels Electric-Arc Process)

	Millions of Canadian Dollars (March 1985)			
Plant Location	Québec		Alberta	
Plant Capacity t/yr (million lb/yr)	22 686 (50)	136 116 (300)	22 686 (50)	136 116 (300)
Direct Capital Investment				
Installed Plant Cost (TPC)	69.06	244.22	71.67	253.43
Project/Estimation Contingency	6.91	24.42	7.17	25.34
Total Installed Plant Cost (TIPC)	75.97	268.64	78.84	278.77
Indirect Capital Investment				
Licence and Prepaid Royalties	1.37	1.50	1.37	1.50
Initial Catalysts & Chemicals	0.10	0.10	0.10	0.10
Start-Up and Other Costs	2.28	8.06	2.37	8.36
Sub-Total	79.72	278.30	82.68	288.74
Working Capital*	2.28	8.06	2.37	8.36
Land*	0.55	0.66	0.57	0.68
Total Capital Investment (TCI)	82.55	287.02	85.62	297.78
Annual Operating, Maintenance and Production Costs (at $7.85/GJ for hydrogen by-product credits)				
Raw Material and Process Input				
Operating Cost	19.44	116.84	18.31	110.08
Overheads	2.73	9.65	2.83	10.02
	26.84	140.60	25.93	134.61
By-products Credits	(9.74)	(58.50)	(8.37)	(52.66)
	17.10	82.10	17.56	81.95
Depreciation	3.99	13.91	4.13	14.44
Capital Recovery Cost	5.44	16.76	5.64	17.38
	26.53	112.77	27.33	113.77
Product Cost, ¢/lb				
at $7.85/GJ H_2 by-product credits	53.1	37.6	54.7	37.9
at $4.74/GJ H_2 by-product credits	117.0	82.8	120.5	83.5
Market Price				
Acetylene, ¢/lb	70 - 80	-	70 - 80	-
Ethylene, ¢/lb	-	19 - 20	-	19 - 20

* non-depreciable items

6.2.3 Conservation of Crude Oil

The use of acetylene as a feedstock for chemical production cannot easily be related to conservation of crude oil since it is not directly produced in Canada from crude oil or its derivatives; acetylene is only an intermediate product and not all end-products derived from acetylene are currently made from crude oil or its derivatives.

On the other hand, the use of acetylene may be linked to the substitution of ethylene which is produced, for instance, by Petromont in Québec from cracking of butane and light naphtha derived from crude oil. It must also be recognized that over 5% of all oil used in USA is consumed by the petrochemical industry with ethylene as a feedstock for a variety of chemicals [110].

If it is assumed that acetylene would substitute ethylene as a feedstock for commodity chemical (e.g., vinylchloride), although the economics are not favourable at the present time, a 300-million lb/yr acetylene production from electric-arc process would constitute a conservation of 6500 billion Btu/yr, or about 1 million bbl/yr of crude oil equivalent.

6.3 HYDROCARBON AND CHEMICAL PRODUCTION FROM COAL VIA ACETYLENE

6.3.1 Acetylene Production from the AVCO Arc-Coal Process

In the late 1950s, AVCO initiated a development program to convert coal to acetylene by using the electric-arc plasma gas heating technology developed earlier by AVCO for material-testing work in a re-entry vehicle plasma environment. Several reactor concepts were tested under contract with the Office of Coal Research (now Department of Energy). The results of these tests

indicated that the suitable design for the coal feed was a magnetically rotated DC arc reactor [111].

A schematic diagram of a prototype reactor (200 kW) is given in Figure 6-4. The DC arc is struck from a central cathode (K) to an annular anode (F). The arc is rotated at high speed (800 rpm) in a magnetic field, for stabilization.

The pulverized coal is injected into the annulus via the feed port C, where it reacts with hot hydrogen plasma gas to produce mainly acetylene.

The bench-scale reactor was typically operated in the following range of operating conditions: 50 to 180 kW, hydrogen flow rates of 15 to 40 scfm, and coal flow rates of 30 to 120 lb/hr. Acetylene yields and concentration as high as 35 wt% and 15.7 wt% respectively, and a specific energy requirement as low as 4.3 kWh/lb of acetylene were achieved. In addition to the main product acetylene, the AVCO arc-coal process produced as by-products carbon black at a yield of about 10 wt%, and HCN at a yield of 0.2 wt% based on coal fed to the reactor. The coal tested was bituminous from Kentucky, U.S.A.

In 1979, AVCO tested their arc-coal 1-MW reactor, under sponsorship of the U.S. Department of Energy (DOE) [110]. The main objective of the pilot-plant program was to demonstrate the technical feasibility of the process and establish the scale-up parameters.

The pilot plant is now dismantled and the process development program is discontinued due to funding priority and constraints from the sponsoring agency.

6.3.2 Overall Conceptual Plant Configuration of AVCO Arc-Coal Process

Figure 6-5 shows the main processing steps for a conceptual, commercial arc-coal acetylene plant based on the design study made by Blaw-Knox Chemical Plants [112] for the Office of Coal Research. The study included equipment specification and capital and operating cost estimates for a 300-million lb/yr acetylene plant based on Kentucky bituminous coal as a feedstock.

For the present study, capital, operating and production costs are presented for two plant capacities (50 and 300 million lb/yr acetylene) using the Canadian subbituminous coal from Forestburg, Alberta. The Blaw-Knox data have been updated to March 1985 Canadian dollars and adjusted for Canadian conditions.

Essentially, the flow scheme for the AVCO arc-coal process is similar to that described earlier (Section 6.1.1). Additional processing steps required are coal preparation, char processing, acid gas removal and sulphur recovery.

The overall material and energy balance for the AVCO coal-acetylene plant, 300 million lb/yr acetylene, is presented in Table 6-7.

6.3.3 Capital Operating and Production Cost

Capital, operating and production cost estimates for 50- and 300- million lb/yr acetylene plants are summarized in Table 6-8.

The total investment for 50- and 300- million lb/yr arc-coal acetylene plant is $128 and $451 million respectively, which are significantly higher than those for the alternative process plants based on natural gas, primarily due to the additional coal

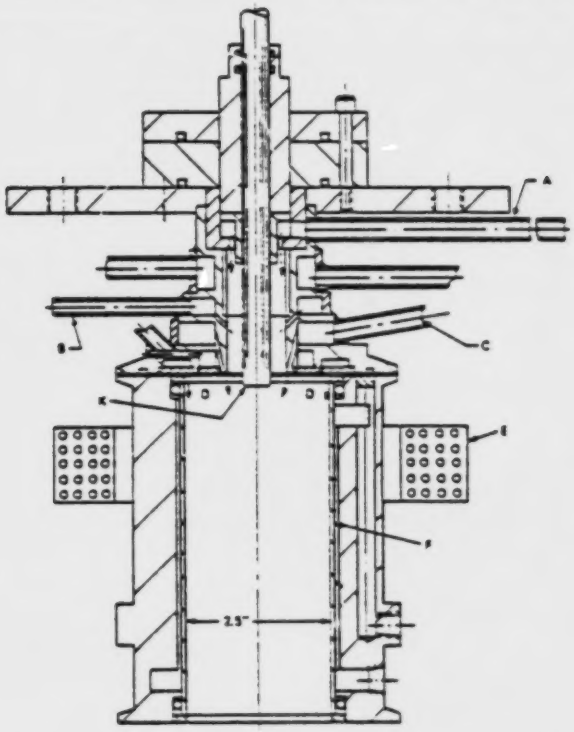

Figure 6-4 AVCO Arc-Coal Acetylene Reaction

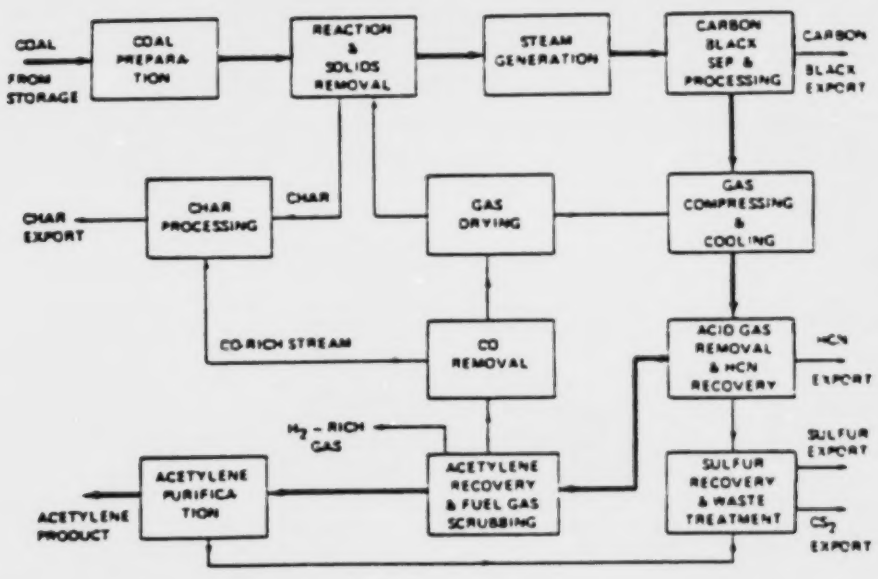

Figure 6-5 Block Flow Diagram for Arc-Coal Acetylene Process

Table 6-7 Overall Material and Energy Balance Summary
(AVCO Arc-Coal Reactor Process)

[Plant Capacity: 300 million lb/yr Acetylene from Coal]

	Flow rate	Unit Quantity per kg of C_2H_2
Raw Material		
Coal	80 580 kg/h	4.74 kg
Propane	21 252	1.25
Electricity, MW		
Arc Reactor	140 MW	8.2 kWh
Plant Use	58.7	3.5
	198.7	11.7
Catalysts and Chemicals	*	*
Other Utilities Required		
** Steam	89 122 kg/h	5.24 kg
Water	962 m^3/h	0.056 m^3
Nitrogen	690 Nm^3/h	0.04 Nm^3
By-products		
Char and Carbon black	29 326 kg/h	1.72 kg
HCN	379	0.022
CS_2	43	0.003
** Fuel Gas	739 GJ/h	43.4 MJ
Products		
Acetylene	17 014 kg/h	-
Ethylene	12 139	0.71

* Quantities and flow rates are not available.

** All the steam is generated in steam boilers by burning fuel gas. For excess fuel gas (383 GJ/h), by-product credits are taken at fuel value

Table 6-8 Capital, Operating and Product Cost Estimates for Hydrocarbon Production from Coal via Acetylene (Plants Located in Alberta) [AVCO Arc-Coal Reactor Process]

Millions of Canadian Dollars (March 1985)

Plant Capacity t/yr (million lb/yr)	Acetylene Plant 22 686 (50)	Acetylene Plant 136 116 (300)
Direct Capital Investment		
Installed Plant Cost (TPC)	100	353.7
Project/Estimation Contingency	20	70.7
Total Installed Plant Cost (TIPC)	120	424.4
Indirect Capital Investment		
Licence and Prepaid Royalties	-	-
Initial Catalysts & Chemicals	0.35	0.7
Start-Up and Other Costs	3.60	12.7
Sub-Total	123.95	437.8
Working Capital*	3.60	12.70
Land*	0.56	0.68
Total Capital Investment (TCI)	128.11	451.18
Annual Operating, Maintenance and Production Costs		
Raw Material and Process Input	13.76	82.48
Operating Cost	10.77	27.89
Overheads	4.47	14.74
	29.00	125.11
By-products Credits	(9.85)	(59.10)
	19.15	66.01
Depreciation	6.20	21.89
Capital Recovery Cost	8.33	29.33
	33.68	117.23
Product Cost		
¢/lb	67.0	39.0
¢/lb	148.0	86.0

* non-depreciable items

processing steps required. Similarly, the final acetylene product cost is also higher, 67¢/lb compared to 55¢/lb for a smaller natural gas - acetylene plant (50 million lb/yr capacity). For a larger plant, the product cost is nearly the same (39¢ compared to 38¢/lb).

CHAPTER 7

POTENTIAL OF PLASMA APPLICATION

IN PRODUCTION OF ADVANCED CERAMIC MATERIALS

7.0 POTENTIAL OF PLASMA APPLICATION IN PRODUCTION OF ADVANCED CERAMIC MATERIALS

Ceramic materials have been produced for centuries and encompass a broad range of inorganic materials. As a general rule, ceramics are better insulators but are more brittle than metals. Ceramics include a wide range of components such as silicates, oxides, carbides, nitrides, sulphides and borides and may be single crystals, polycrystalline, glass-bonded aggregates or wholly vitreous.

According to present use and/or potential applications, ceramic materials can be divided into two groups: the conventional ceramics and the advanced ceramics.

According to the U.S. Department of Commerce (DOC), 1982 Census of Manufacturers [113], the applications of conventional ceramic materials are covered by the following four Standard Industrial Classification (SIC) codes:

322 Glass and Glassware
352 Structural Clay Products
326 Pottery and Related Products
329 Refractories and Abrasives

The latter category has also been called the fused ceramic industry.

Conventional ceramics are manufactured from materials which are abundant in the earth's crust. Clays and quartz are the most widely used raw materials.

Advanced ceramics are made from extremely pure, ultrafine particles formed, sintered and treated under closely regulated conditions. The structure and composition of the materials are highly controlled. As a result, the advanced ceramics tend to have superior properties and performance characteristics as compared to those of conventional ceramics (high strength and hardness, thermal shock resistance, controlled electrical and magnetic properties, high erosion and corrosion resistance, etc.,).

Three routes have been used in developing or formulating advanced ceramic materials [114]:

- Improving properties of conventional ceramics through new processing technological concepts. For example, production of toughened Al_2O_3- and ZrO_2-based ceramics with superior mechanical and structural properties by using microstructural control, transformation toughening and hot isostatic pressing technique;

- Application or development of new materials composition which inherently possess superior properties. These materials may be processed using conventional and/or new processing techniques. Silicon nitride (Si_3N_4), partially stabilized zirconia ($ZrO_2 \cdot Y_2O_3$), sialon ($Si_3Al_xN_yO_2$) are examples of such new ceramic materials;

- Application or development of composite materials in order to achieve the desired properties. In this route, both metal-in-ceramic and ceramic-in-metal materials have been developed. The dispersed metal toughened (DMT) technique has been used to increase the toughness of alumina ceramics (continuous phase) using chromium and/or platinum fine

particles (dispersed phase). The use of ceramic fibres to reinforce metal (e.g., reinforce aluminum with alumina fibres for connecting rods or automobile applications) is an example of ceramic-in-metal composite material.

A new era has been opened in the development and applications of advanced ceramics due to their superior thermal, chemical, mechanical and electrical properties. Some advanced ceramic materials and their current or potential applications are shown in Table 7-1.

Table 7-1 Current or Potential Applications of Some Advanced Ceramic Materials

Material	Major Properties	Applications
Alumina (Aluminum Oxide, Al_2O_3)	Electrically insulating hardness, corrosion resistance	Electronic insulators, wear parts
Aluminum Silicates	Insulator	Heat engines
Silicon Carbide (SiC)	Hardness	Heat engines, wear parts
Silicon Nitride (Si_3N_4)	Thermal shock resistance	Heat engines
Sialon (Si-Al-O-N)	Fracture toughness, hardness, strength	Heat engines
Zirconia (ZrO_2)	Conductor	Electronic sensors, heat engines
Titanates (e.g., $BaTiO_2$)	Insulator, piezoelectric	Electronic capacitors
Composites Ceramic fibers in ceramic, metallic or organic matrix	Toughness, strength	Heat engines

Note: Heat engine parts refer to such parts as pistons, cylinder liners, turbocharger rotors, etc. Wear parts include bearings, pump components, seals, etc.

Advanced ceramics are also called high-performance or modern ceramics, in Japan, they are called "fine ceramics" (the term "fine" is used due to the fineness of the powders). Also, when advanced ceramic materials are used in a machine component, they are termed structural or engineering ceramics.

Advanced ceramics with other advanced engineering materials (composites, reinforced plastics, graphite fibres) have the potential to replace the more traditional engineering materials such as wood and metals. Particularly great interest in engineering ceramics comes from their potential future use in heat engines, gas turbines, diesel and gasoline engines. Also, there are many current important applications, which offer immediate market opportunity for advanced ceramics (e.g., cutting tools, wear or abrasive parts, electronics).

The value of advanced ceramics shipped in the U.S.A. in 1980 was US $ 743 million (see Table 7-2). The largest portion was for end-use in electronics (about 88%). The projected value growth of advanced ceramics shipment in the U.S.A. is about tenfold in 20 years (US $ 7290 million in the year 2000) with the share of ceramics used in heat engines increased in value to 15% (from 0% in 1980) [115].

The estimated sales of advanced ceramic materials worldwide by 1995 is above 10 to 12 billion dollars [114]. Due to the projected large market potential, international competition to capture a share of such a market is severe. Almost all major car makers worldwide have active programmes on the development and use of components made from advanced ceramics (e.g., Ford and General Motors in the U.S.A., Volkswagen and Daimler-Benz in F.R.G., Volvo and Saab in Sweden, Leyland in the U.K., Isuku and Toyota in Japan).

Table 7-2 Projected U.S. Shipment of Advanced Ceramics
(in Millions of 1984 Dollars)

End-Use	1980		1990		2000	
	Value	%	Value	%	Value	%
Electronics	660	88	2349	75	4309	59
Cutting Tools	56	7.5	470	15	1187	16
Wear Parts	25	3	223	7	668	9
Heat Engines	0	0	69	2	1039	15
Other	2	0.5	19	1	87	1
Total	743	100	3130	100	7290	100

Source: Industry Analysis Division, "A Competitive Assessment of the U.S. Advanced Ceramics Industry", U.S. Dept. of Commerce, Washington, DC, Report No. PB84-162288, March 1984.

National programs on advanced ceramics research, development and demonstration (RDD) have been undertaken in Japan, United States, F.R.G., U.K., France and Sweden. A joint program supported by European Economic Community (EEC) is also underway [116].

Intensive research has been conducted on the design and fabrication of engine and ceramic wear parts in both the United States and Japan. The U.S. Dept. of Commerce estimated that over US $ 250 million was spent between 1971 and 1983 on ceramic research for vehicular engines alone [117]. Table 7-3 summarizes the 1985 fiscal year (October 1984 to October 1985) federal government spending on advanced ceramics for heat engines alone. For the same period, the total government spending on structural ceramics is estimated to be US $ 50 million [117]. In

terms of privately-funded R & D, there are numerous firms involved in ceramic engineering parts research. If, as is usual, privately-funded R & D matches that of the federal government, then over $ 100 million is currently being spent in the United States each year.

Table 7-3 U.S. Research and Development Programs in Heat Engine Ceramics (Funding in Thousands of Current Year Dollars)

Agency	Program	FY 1984	FY 1985
Department of Energy:			
. Oak Ridge National Laboratory	Ceramic technology for advanced heat engines	950	1750
. NASA/Lewis Research Center	Heavy duty transport technology	747	178
Department of Defense:			
. Army (TACOM)	Adiabatic diesel engines	157	200
. Navy (NRL)		480	425
. Air Force		153	0
		2,487	2,553

Source: E.M. Lenoe, J.L. Meglen, "International Perspective on Ceramic Heat Engines", Ceramic Bulletin, Vol. 64, No. 2, 1985.

Japan has embarked on an ambitious program to develop ceramic parts for heat engines. The estimated industrial R & D spending in Japan in 1985 is around US $ 400 million with growth forecasts showing expected sales of fine ceramics to exceed US $ 3.6 billion by 1990 [116]. The Japan Ministry of International Trade and Industry (MITI), estimated that by 1990,

between 500 and 600 firms will belong to the Japan Fine Ceramics Association. Research is also continuing in the Federal Republic of Germany. The current funding is shared by industry and the government with industry supplying over 50% of the funds [116].

In Canada, industrial activity in advanced ceramics is very limited. Several small ceramic companies are manufacturing piezoelectric ceramics and other industrial specialty ceramics. Companies such as Pratt and Whitney, Canada and IBM have in-house programmes on advanced ceramics. Similar to the situation in the U.S.A. and Japan, some Canadian corporations and subsidiaries of multi-national companies in Canada might be interested in advanced ceramics because of the availability of relatively low cost electricity and raw materials resources.

Based on the scenario that the projected market potential will be realized, the estimated tonnage of engineering ceramic powder for the Canadian automobile market alone may be as high as 15 000 tonnes per year. The Canadian electrical load projection for production of ceramic auto parts would be between 22.5 MW to 1845 MW depending on cost competitiveness of these parts. These projected electrical loads would result from both the production of ceramic powders and subsequent processing of these powders to the final ceramic components [116].

Some candidate Canadian Companies having opportunities in Engineering Ceramics are listed below: [116]

General Motors of Canada	Alcan
Ford of Canada	Inco
Stelco	Noranda
Dofasco	Cominco

Lasco	Falconbridge
Iron Ore Company of Canada	Sherritt-Gordon
Pratt & Whitney	Northern Telecom
Babcock & Wilcox	Rolls-Royce Motors
Norton	SKF
Ferro Corporation	Sandvik, Canada
General Abrasives	IBM
Carborundum	Blue Mountain Hi-tech
Union Carbide	Hamilton Porcelain
Dupont	W.R. Grace
Dow Chemical	ASEA
General Electric Canada	Magna International
Westinghouse	Almax Industries Ltd.

This is by no means an exhaustive list of Canadian companies having their products affected by engineering ceramics.

7.1 POTENTIAL PLASMA APPLICATIONS IN PRODUCTION OF ADVANCED CERAMIC MATERIALS

There are numerous technological steps between collection of raw materials and the final product as a finished ceramic part. The major steps are:

- **Powder production and powder particle sizing;**
- **Pre-consolidation processing** by mixing and processing of powder with additives (binders, lubricants, sintering and flow additives, etc.,).
- **Forming** to desired shape and close dimensions of the final part by pressing, casting or plastic forming. After forming, the parts are called "green" bodies.

- **Sintering** of the green body at controlled temperature and atmospheric conditions to achieve maximum possible densification. Sintering is essentially the removal (reduction) of pores in the material accompanied by an increase of amount and strength of molecular bonds resulting in a high-strength, well-bonded material. Sintering can occur via vapor, liquid- or solid-phase transport and is accompanied by a decrease in the volume of the part. The sintering temperature is about 1500° to 2000°C [119].

- **Machining** of the sintered material to produce a net shape of ceramic part with desired tolerances and surface finishes, as well as removing surface flaws. Ceramic materials are difficult to machine because they are both hard and brittle. Therefore, the standard metal cutting tools and techniques are usually not applicable and mechanical abrasive techniques are mostly used for machining of engineering ceramic parts. Also chemical, electrical methods, laser and photo etching techniques can be used for machining.

- **Post machining** is required for final treatment of ceramic parts to polish the surface and remove defects or stresses. Mechanical or flame polishing, annealing, oxidation, chemical etching, surface compression are the techniques used for post machining treatment of engineering (structural) ceramic parts.

The key aspect in production of advanced ceramic materials are the critical processing-microstructure-property relationships, since the properties exhibited by a ceramic are controlled, to a large extent, by the fabrication process. The present manufacturing costs of structural ceramics to be used, for example, in an injection-molded turbocharger rotor is above US $100/kg. Such relatively high cost is mostly because of

expensive post-sintering hot isostatic pressing cycles used to achieve the required high densities and mechanical properties of the materials.

The processing steps and cost vary with specific properties required for each component, yet the cost for a typical structural ceramic part generally falls into the five categories shown in Table 7-4 [118].

Table 7-4 Manufacturing Cost Breakdown for Structural Ceramics and High-Value-Added Advanced Metals and Polymers

Category	Structural Ceramics Cost %	Advanced Metals and Polymers Cost %
Raw Materials	5 - 10	30 - 60
Forming (Mixing, shaping)	5 - 10	10 - 20
Sintering (Firing)	10 - 15	10 - 20
Machining (Finishing)	30 - 50	5
Post Machining (Rejection)	40 - 60	5 - 10

Source: Barringer, G.A. and Bowen, H.K., Ceramic Powder Processing, Report No. 34, Ceramic Processing Research Laboratory, MIT, Mass., March 1984.

It may be seen that structural ceramics require expensive finishing (machining and post-machining) steps which can amount to 75 to 80 per cent of the total manufacturing cost (e.g., in case of ceramic turbocharger rotors) [118]. This is due to non-reliable processing during previous technological steps

(e.g., lack of net-shape densification which necessitates extensive machining/post machining). Impure, agglomerated starting powders and wide particle size distribution causing green body microstructure heterogenetics are the single largest factor contributing to the high cost of finishing steps. It is especially true if taking into account that a typical ceramic component is formed from more than 10^{12} particles/cm^3 [119].

In Table 7-4 above, the manufacturing cost breakdown for advanced ceramics is compared to that for existing high-value-added advanced metals and polymers (plastics) in which raw materials comprise a major portion of the cost. If, in future, processing technologies will be more reproducible and reliable, and near-shape sintering or casting could be achieved, the advanced ceramics manufacturing cost distribution would be similar to that of other advanced materials (e.g., advanced metals and plastics) and may be reduced correspondingly from US $100/kg down to the US $20 to 30/kg range [118].

To reduce substantially the machining/post machining operations and costs, the starting powder should consist of pure, non-agglomerated, fine (dia = 0.1 to 1.0 micron) particles with a narrow size distribution and equiaxed shape [121]. **Application of plasma synthesis may be the one of most appropriate ways to achieve this goal, as has been shown in a number of experimental investigations carried out in several countries worldwide on production of advanced ceramic powders as well as metal powders** (e.g., in the U.S.A. [120, 121, 122, 123, 124], Japan [125, 126], Switzerland [127, 128], F.R.G. [129], U.K. [130], U.S.S.R. [131], Italy [132] and many others).

Plasma spheroidization of coarser nonspherical particles from high melting temperature materials is another approach to produce fine, equiaxed powders. This method is being investigated, in particular at the University of Sherbrooke [3] and Ontario Hydro Plasma Centre jointly with several Canadian industrial companies [1].

Plasma sintering of advanced (structural) ceramic materials has also been reported recently [133].

Hence, thermal plasma applications for production of advanced ceramic powders may have a great industrial potential in Canada and worldwide. It should be noted, however, that all the experimental investigations in this area, on which technical data are available, were carried out on a relatively small laboratory scale and that many problems have to be solved before commercialization of plasma technology can be applied to advanced ceramic production. Therefore, this plasma application should be considered as a long-term development.

An intensive R & D strategy is recommended for Canada, targeted toward commercial applications of plasma technology in production of advanced ceramic powders around 1990-1995 when tremendous market opportunities in advanced ceramics are expected.

REFERENCES AND SOURCES

REFERENCES AND SOURCES

1. Mikhlin, J.A., Report on visit to IREQ (Hydro-Québec), Ontario Hydro and IMRI Plasma Centres, Technical Development Department, SNC; November 1984.

2. Gauvin, W.H., Kubanek, G.R., U.S. Patent 466,023; April 1984.

3. Mikhlin, J.A., Report on visits to University of Sherbrooke, McGill University and University of Toronto Plasma Centres; Technical Development Department, SNC; October 1984.

4. Direct Iron Smelting - A Pilot Plant, Institut de Recherche d'Hydro-Québec (IREQ) Proposal, (prepared by Drouet, M.G. in collaboration with Naden D., Davy McKee R & D and Dancy, E., IREQ); September 1984.

5. Kershaw, P. and Naden, D., "The Development of Integrated Ore Pre-Reduction and DC Transferred-Arc Plasma Smelting Technology for Iron and Ferro-alloys Production"; Proceedings, 7th International Symposium on Plasma Chemistry, ISPC-7; Eindhoven, The Netherlands; July 1985.

6. Alcock, C.B., McLean, A., Sommerville, I.D., "An Extended-Arc Reactor Using Graphite Electrodes", Preprint, MINTEK 50; Randburg, South Africa; Paper C5/2; March 1984.

7. McLean, A., Private communication on IMW demonstration plasma facility based on University of Toronto Extended-Arc Plasma Reactor; June 1985.

8. Ettlinger, L.A., Nainan, T.D., Ouellette, R.P., Cheremisinoff, P.N., "High-Temperature Plasma Technology Applications"; Electrotechnology 6; 1980.

9. Frank-Kametskii, D.A., "Plasma, the Fourth State of Matter", Plenum Press; N.Y.; U.S.A. 1972.

10. Foster T., and Liu, G., "Plasma Arc Heater Design - Techniques for Commercial Process Applications"; Conference on Electrotechnologies in Industry; Montréal, Québec, Canada; May 25-27, 1982.

11. Bebber, H.J., Neuschütz, D., and Rossner, H.-O., "Entwicklungsstand der Drehstrom-Plasmatechnik bei Krupp"; Metall 39. Jahrgang, Heft 4; April 1985.

12. Thunberg, S.L., Melilli. W.J., and Reed, W.H., Westinghouse Applied Plasma Systems; Can Inst Min Met, 85th Annual General Meeting; Winnipeg, Manitoba; Canada, April 17-20, 1983.

13. Fey, M.G., "Plasma Technology for the Steel Industry"; Westinghouse Electric Corp.; Assoc Iron Steel Eng. Convention; Toronto, Ontario, Canada; October 16, 1984.

14. a) "Plasma Arc Heater", Aérospatiale, France, 1985.
b) "Patri, G., "Révolution tranquille à Boulogne-sur-mer", Revue Aérospatiale 14:27-30; November 1984.

15. Camacho, S.L., "Plasma Arc Torch Technology - Its Technical Merits and Application Potentials"; Plasma Energy Corporation, Presentation to members of the Club Électricité de France; Bollène, France; May 17, 1984.

16. Herlitz, H.G., and Santen, S.O., "Production Experience with Plasma Technology in Metallurgical Processing"; Assoc Iron Steel Eng Annual Convention; Toronto, Ontario, Canada; October 16, 1984.

17. Skogberg, J., Seminar "Today's Energy for Tomorrow"; Montréal, Québec, Canada; January 1985.

18. Gladish, H., "How Huels Makes Acetylene by DC Arc"; Hydrocarbon Process Pet Refiner 41:6:159; June 1962.

19. Mikhlin, J.A., Report on visit to Volcano Inc., Québec; Technical Development Department, SNC; March 1985.

20. Camacho, S.L., Private Communications; July 1985.

21. MacRae, D.R., "Plasma Metallurgy and Other Thermal Plasma Applications"; Short Course on Fundamentals and Applications of Plasma Chemistry; University of Minnesota; Minn., U.S.A.; June 16-19, 1981.

22. Fey, M.G., and Kemeny, G.A., "Method of Direct Ore Reduction Using a Short Gap Arc Heater"; U.S. Patent 3,765,870; October 18, 1969.

23. Tylko, J.K., "High Temperature Treatment of Materials", U.S. Patent 3,783,167; January 1, 1974.

24. MacRae, D.R., "Plasma Processing in Extractive Metallurgy: The Falling-Film Reactor"; Am Inst Chem Eng Symp Ser 186:75:25-30; 1979.

25. MacRae, D.R., Gold, R.G., U.S. Patent 4,234,334; November 18, 1980.

26. Gauvin, W.H., "Application of Plasma Technology to the Production of Strategic Metals"; In: Can Elect Assoc Research Report 126 U 322; March 1984.

27. Gauvin, W.H., Kubanek G.R., Mehmetogly M.T., and Choi H.K., "Operating Characteristics and Engineering Applications of Transferred Arcs"; Proceedings, 5th International Symposium on Plasma Chemistry, ISPC-5; Edinburgh, Scotland; August 1981.

28. Pickles, C.A., McLean, A., Alcock, C.B., Segsworth, R.S., "Graphite Electrode Phasing Furnaces and Their Application for Iron and Steelmaking"; International Conference on the Physical Chemistry of Iron and Steelmaking, 1979.

29. Pickles, C.A., and Alcock, C.B., "Production of Ferronickel and Ferrovanadium from Fly Ash in an Extended-Arc Flash Reactor"; J Met; December 1983.

30. Plasma Processing of Materials, Report of National Materials Advisory Technical Board, Commission on Engineering and Technical Systems, National Research Council, Washington D.C., U.S.A.; 1985.

31. MacRae, D.R., Gold, R.G., Thompson, C.D., and Sandall W.R., "Ferrovanadium Production by Plasma Carbothermic Reduction of Vanadium Oxide"; Proceedings, 34th Electric Furnace Conference; Iron Steel Soc Am Inst Min Eng 34; 1976.

32. Camacho, S.L., "Power Energy Corporation Plasma Arc Torch Technology - Its Technical Merits and Application Potentials"; Middle South Industrial Marketing Conference; New Orleans, La., U.S.A.; June 5, 1984.

33. Gauvin, W.H., and Choi, H.K., "Plasma in Extractive Metallurgy", Paper presented at Annual Meeting of the Materials Research Society, Boston, Mass., U.S.A.; November 1983.

34. Roman, W., United Technologies Corp., Private communication; 1983.

35. Lugscheider, W., "Plasma Furnace Projects for Economical Production of Steel and of Ferroalloys in the Voest-Alpine-Group", Symposium on Industrial Opportunities for Plasma Technology; Toronto, Ontario, Canada; October 21, 1982.

36. Lugscheider, W., "Voest-Alpine's Plasma Plant", Voest-Alpine, Austria; Metal Bulletin, Monthly 150:45-49; June 1983.

37. Reid, K.J., "Plasma Metallurgy in the 80s"; Preprint, MINTEK 50; Sandton, South Africa; March 1984.

38. Neuschütz D., Robner, H.-O., Bebber H.J., and Hartwig J., "Development of Three-Phase AC Plasma Furnaces at Krupp"; Iron Steel Eng.; May 1985.

39. Cowx, P.M., Heanley C.P., "The Melting and Refining of Metallic Ferroalloy Fines in the Tetronics Furnace", Proceedings, 7th International Symposium on Plasma Chemistry, ISPC-7; Eindhoven, The Netherlands; July 1985.

40. Page, D.G., Heanley, C.P., Cowx P.M., "The Extraction of Non-Ferrous Metal with the Tetronics Plasma System, with Particular Emphasis on Zinc and Lead"; MINTEK 50; Sandton, South Africa; March 1984.

41. Harry, J.E., and Knight, R., "Multiple Arc Discharge for Metallurgical Reduction or Metal Melting"; Mater Res Soc, Symposium on Plasma Processing and Synthesis of Materials; Boston, Mass., U.S.A.; 1983.

42. Barcza, N.A., Curr, T.R., Winship, W.D. and Heanley C.P., "The Production of Ferrochromium in a Transferred-Arc Plasma Furnace"; Proceedings, 39th Electric Furnace Conference; Iron Steel Soc Am Inst Min Eng 39:243-260; 1982.

43. Bhat, G.K., "Technical and Commercial aspects of Plasma Heat Applications in primary melting, secondary remelting and refining operations" J Vac Sci Tech 18:3; 1981.

44. Dancy, E. "Application of Plasma Technology in Iron and Steel Industry"; In: Can Elect Assoc Research Report No. 126 U 322; March 1984.

45. Ponghis, N., Vidal, R., Poos, A., "Operation of a Blast Furnace with Superhot Reducing Gas", Centre de recherche Métallurgique 56:9-15; June 1980.

46. Ponghis, N., Vidal, R., Poos, A., "PIROGAS - A New Process Allowing Diversification of Energy Sources for Blast Furnaces"; High Temp Technol 1:5; August 1983.

47. Ponghis, N., Vidal, R., Poos, A., (CRM), Injection au haut fourneau de gaz réducteurs produits en million plasmatique: Le procédé Pirogas, Revue de Métallurgie - CIT; Juillet 1983.

48. Down, M.G., "Plasma Processing for Materials Production", Electric Power Research Institute Report, EM2771; Dec. 1982.

49. "Les hauts fourneaux d'Uckange négocient pour des Torches à Plasma", Bulletin Quotidien Enerpresse 3737:10; January 7, 1985.

50. Mikhlin, J.A., Report on Visit to Aerospatiale Plasma Centre; Technical Development Department, SNC; 1985.

51. Graffeuille, P., Allaire B., and Lao D., "Coal Injection Practice in Usinor Dunkirk BF.2"; Iron Steel Soc; 1984.

52. Lankford, W.T., Samways, N.L., Craven, R.F., McGannon, H.E., (Editors); "The Making, Shaping and Treating of Steel", United States Steel, Assoc Iron Steel Eng; Pittburgh, Penna., U.S.A.; 10th Edition; 1984.

53. Mikhlin, J.A., Report on Visit to Sidbec-Dosco; Technical Development Department, SNC; November, 1984.

54. Technical Information, Union Steel Corporation (USCO); South Africa; 1984.

55. Mikhlin, J.A., Report on visit to Chemische Werke Hüls AG; Technical Development Department SNC; July, 1985.

56. Gold R.G., Sandall W.R., Cheplick P.G., and MacRae D.R., "Plasma Reduction of Iron Oxide with Hydrogen and Natural Gas at 100 kW and 1 MW"; Ironmaking and Steelmaking:1; 1977.

57. Amouroux J., Codron J.L., and Morvan D., Revue générale de l'électricité 87:6; 1978.

58. Edström J.O., "Smelting Reduction Processes: Economic Viability"; United Nations, Economic Commission for Europe; Transmitted by Government of Sweden, Royal Institute of Technology, Stockholm, Sweden; May 1983.

59. Fatum J.H., "MESABI Metal Project"; Am Inst Chem Eng., Minnesota Section, 58th Annual Meeting; January 16, 1985.

60. Davis, C.G., McFarlin, J.F., and Pratt, M.R., "Compilation of Reports on Direct Reduction Technology and Economics"; U.S. Dept. of Energy, Report IDO-10095; June 1985.

61. Avrantchev, L., Lebel-Drolet, S., "Inventaire des Gisements Minéraux du Québec"; Ministère de l'Énergie et Resources Québec, Canada; Septembre, 1979.

62. Walker, L.A. Luhning, R.W., Rashid, K., "Potential for recovering vanadium from Athabasca tar sands"; Symposium on Tar Sands, 26th Canadian Chemical Engineering Conference; Toronto, Ontario, Canada; October 1976.

63. Lemay, L., "The Canadian Mineral Industry: Review and Outlook"; Bokolay, G. and Lalande, M., "Regional Mineral Developments", Can Min J 105:2; 1984.

64. Barcza N.A., Curr J.A., Maske K.V., "The Application of Thermal Plasma Technology to Large Scale Pyrometallurgical Processes"; Extraction Metallurgy'85; London, England; September 1985.

65. Maske, K.V., "The Reduction of Chromite in a Transferred-Arc Plasma Furnace"; MINTEK Report 1178; January 1985.

66. Hamblyn S.M.L, "Plasma Technology and Its Application to Extractive Metallurgy"; Miner Sci Eng 9: 3: 151; 1977.

67. Flink, B., Herlitz H., Johanson, H., Santen, S., "Pilot Plant Experience of SKF Steel's Plasma Technology for Ferroalloy Production"; SKF Steel Engineering AB, Sweden; March 1985.

68. "SKF Steel's Plasma Technology Quality Improvement and Cost Reduction"; SKF Steel, Technical Report 1/1984.

69. Mikhlin, J.A., Report on visit to SKF Steel, U.S. Headquarters in Avon, Conn.; Technical Development Department, SNC; March 15, 1985.

70. Gauvin, W.M., Kubanek, G.R., Irons, G.A., "The Plasma Production of Ferromolybdenum - Process Development and Economics"; J Met 33:1; 1981.

71. Munz, R.J., Gauvin, W.H., "The Decomposition Kinetics of Molybdenite on in Argon Plasma"; Am Inst Chem Eng J Met 21:6; 1975.

72. Gauvin, W.H., Personal communication, June 1975.

73. Liang, A. and Munz R.J., "Ferrochromium Production by Plasma - Technology Techno-Economic Assessment"; Proceedings, 6th International Symposium on Plasma Chemistry, ISPC-6; Montréal, Canada; July 1983.

74. Taniuchi, K., Mimura, K., "Arc-plasma Reduction of Tantalum Oxide with Carbon"; Proceedings of the Australia/Japan Extractive Metallurgy Symposium; Sydney, Australia; July 1980.

75. Biceroglu, O. and Gauvin, W.N., "Chlorination Kinetics of Zirconium on in R.F. Plasma Flame", Am Inst Chem Eng J 26:5; 1980.

76. Biceroglu, D. and Gauvin W.N., "The Chlorination Kinetics of Zirconium Dioxide on the Presence of Carbon", Can J Chem Eng 58; June 1980.

77. Bunting K.A., "Sodium and Titanium Tetrachloride Feed System for a Plasma Route to Titanium"; Proceedings, 6th International Symposium on Plasma Chemistry, ISPC-6; Montréal, Québec, Canada; July 1983.

78. The Tioxide Group Technical Bulletin, 1985.

79. Noranda Sales Corp. Ltd., Direct Communications, September 12, 1985.

80. Electric-Arc Steelmaking Review, "Metals and Materials", April 1981.

81. Lugscheider, W., "Utilisation du four à plasma en acierie électrique"; Voest-Alpine, Austria, Journal du four électrique 10:29-33; 1981.

82. Bhat, G.K., "New Developments in Plasma Arc Melting"; J Vac Sci Tech 9:13-44; 1972.

83. Schoukens, A.F.S. and Curr, T.R., "The Production of Manganese Ferroalloys in Transferred-arc Plasma Systems"; MINTEK 50; South Africa; 1983.

84. Stenkist, S.E., "Ladle Furnace with DC Heating", S.A. Patent 83/6659, Assignee ASEA AB; Sweden; September 7, 1983.

85. Lugscheider, W. and Haraldson, S., "Immersed Arc Heater", Proceedings, 40th Electric Furnace Conference, Kansas City, December 1982, Iron Steel Soc Am Inst Min Eng 40:251-255; 1983.

86. Miller, S.A., "Acetylene - Its properties, Manufacture and Uses", Academic Press; N.Y., U.S.A., 1966.

87. Doukas, G., Dupont de Nemours E.I. and Company, "Process for Making Acetylene"; U.S. Patent 3,073,769; January 15, 1963.

88. Cichelli, M.T., and Schotte, W., Dupont de Nemours E.I. and Company, "Manufacturer of Acetylene"; British Patent 938,823; October 9, 1963.

89. Müller, R., Chemische Werke Hiils, "Information for an Economic Evaluation of the Huels Process for the Production of Acetylene"; Report to SNC Inc., Ref. No. 1050/98-BU; December 23, 1983.

90. Beiers, H.G., Baumann, H., Bittner, D., Klein, J., "Experiments on the Pyrolysis of Coal is Arc-Heated Hydrogen", Proceedings, 7th International Symposium on Plasma Chemistry, ISPC-7; Eindhoven, The Netherlands; July, 1985.

91. Gauvin, W.H., Duncan, S.R., "Methanol From Peat Using Plasma-Generated Superheated Steam"; Noranda, Québec, Canada; December 1982.

92. Simonsen H.I., "Economic Feasibility of Wood Gasification Using a Plasma Pyrolysis Reactor"; Energy, Mines and Resources Canada; Report for PAPRICAN; March 1985.

93. Tedeschi, R.J., "Acetylene - Based Chemicals from Coal and Other Natural Resources"; Marcel Dekker, Inc.; N.Y., U.S.A.; 1982.

94. Cooke, N.E., Ashraf, F.A., "Conceptual Design and Techno-Economic Assessment of Three Electricity-Based Reactor Processes for Production of Liquid Fuels and/or Hydrocarbons from Natural Gas"; SNC Inc., Report for CANMET; March 1985.

95. Spiers, J.A.L., British Hydrocarbon Chemicals Ltd., "The Selective Hydrogenation of Acetylene in Ethylene Made by the Steam Cracking Process"; Catalysis in Practice; Inst Chem Eng; 1963.

96. Tabak, S.A., Mobil Research and Development Corporation, "Production of Synthetic Diesel Fuel from Light Olefins"; Am Inst Chem Eng National Meeting; Philadelphia, Penna., U.S.A.; August 2, 1984.

97. Kanugi T., Tanura, T. and Naito, T., "New Acetylene Uses Hydrogen Dilution", Chem Eng Prog 57:11:43; 1961.

98. Fey, M.G., and Reed, W.H., Westinghouse Electric Corp., "Arc Heater Pyrolysis of Hydrocarbons", Am Inst Chem Eng, National Meeting, Philadelphia, Penna., U.S.A.; June 1980.

99. "Arc-coal Acetylene Process Development Program - Phase IB"; AVCO Systems Division (contract No. AC07-79-C-S40214) for U.S. Dept. of Energy, Report No. DOE/CS/40214-T1, April 1981.

100. Muller, R. and Peuckert, C., "Recent Developments for the Production of Acetylene from Coal by the Huels Arc Process"; Proceedings, 6th International Symposium on Plasma Chemistry, ISPC-6; Montréal, Québec, Canada; July 1983.

101. Happel, J. and Kramer, L., "Selective Pyrolysis of Methane to Acetylene and Hydrogen"; U.S. Patent 3,156,733; November 10, 1964.

102. Happel, J. and Kramer, L., "Acetylene and Hydrogen from Pyrolysis of Methane", Industrial and Engineering Chemistry 59:1:39-50; 1967.

103. Helgesen, H.P., Holmen, A. and Langeland, O., "SINTEF Petrochemical Processes - The Production of Acetylene"; Report for: Norwegian Technical Natural Science Research Council, Report No. B.1247, June 1967.

104. Holmen, A., et al., "High Temperature Pyrolysis of Hydrocarbons - Methane to Acetylene", Industrial and Engineering Chemistry 15:3; 1976.

105. Holmen, A., Scientific and Industrial Research Foundation (SINTEF), The Norwegian Institute of Technology, University of Trondheim, Norway; Information Package to SNC Inc., Report No. 21/AH/bde, January 20, 1984.

106. Mikhlin, J.A., Divanji H., Ashraf F.A., "Technology Assessment of the Processes for Direct Liquefaction of Onakawana Lignite"; Phase I & II, SNC Inc., Report for Ontario Ministry of Energy; March 1984.

107. Mikhlin J.A., Ashraf F.A., Dhawan, J.A., Khandhadia P., Pienkowski J., "Study Relating to the Technical and Economic Feasibility of Lignite Liquefaction in Saskatchewan"; SNC Inc., Report for Saskatchewan Oil and Gas Corp. and CANMET, Vol. 1-4, Oct. 1982.

108. McGreevey, T.H., "Chemical Economics Handbook, Acetylene", Ref. No. 605.5021, A-V, August 1975, Stanford Research Institute (SRI), Menlo Park, California, U.S.A.

109. Müller R., Chemische Werke Hüls, "Information Package for an Economic Evaluation of the Huels Process for the Production of Acetylene"; Report to SNC Inc., Ref. No. 1050/08-BU, December 23, 1983.

110. Wragg J.G., et al., "Arc-coal Acetylene Process Development Program, Phase 1B", AVCO System Division Report for U.S. Dept. of Energy, September 1980

111. Gannon, R.E., Krukonis V., "Arc-coal process development"; Office of Coal Research, R & D Report No. 34, 1972.

112. Office of Coal Research, U.S. Dept. of Interior, R&D Report No. 67 (Final), Blaw-Knox Chemical Plants, Inc., "Review and Evaluation of 300 MM lbs/year Acetylene Plant AVCO Arc-Coal Process"; November 30, 1971.

113. U.S. Department of Commerce, 1982 Census of Manufacturers: Vol. 1. "Summary and Subject Statistics", Washington, D.C., U.S.A.

114. Sanders, H.J., "High-tech Ceramics", Chem & Eng N, 62:28, 1984.

115. U.S. Department of Commerce, "A Competitive Assessment of the U.S. Advanced Ceramic Industry"; Report No. PB84-162288, Washington, D.C., U.S.A.; March 1984.

116. "State-of-the-Art on Engineering Ceramics and the Potential in Canada"; Report prepared by Ontario-Hydro Research Division for the Canadian Electric Association; February 1985.

117. Lenoe, E.M., Meglen, J.L., "International Perspective of Ceramic Heat Engines", Ceramic Bulletin 64: 2; 1985.

118. Barringer, E.A. and Bowers, H.K., "Ceramic Powder Processing", Report No. 34, Ceramics Processing Research Laboratory MIT, Mass., U.S.A; March 1984.

119. Barringer, E.A., Jubb, N., Fegley, B., Pober, R.L. and Bowen, H.K., in "Ultrastructure Processing of Ceramics, Glasses and Composites", Hench, L. and Ulrich, D.R. (Editors) Wiley; N.Y., U.S.A., 1984 pp. 315-33.

120. Shipp, P., Pfender, E., "Controlled Generation of Sub-Micron Metallic Particles in a Plasma Jet", Am Inst Chem Eng, 82nd National Meeting, Atlantic City, Ga., U.S.A.; August-September 1976.

121. Selover T.B., Jr., "Properties of nickel fume generated in a plasma jet"; Am Inst Chem Eng J 10; 1964.

122. Wilks P.H., Lacroix D.R., "Preparation of Ultrafine Particles from Volatile Chlorides in Plasma"; 2nd International Conference on Fine Particles, Boston, Mass., U.S.A.; October 1973.

123. Salinger, R.M., "Preparation of Silicon Carbide from methylchlorosilanes in a Plasma Torch"; Ind Eng Chem Prod Res Dev 11; 1972.

124. Kong, L., Huang, T.T., Pfender, E., "Synthesis of silicon carbide in a thermal plasma", Proceedings, 6th International Symposium on Plasma Chemistry, ISPC-6; Montréal, Québec; July 1983.

125. Yoshida, T., Eudo H., Saito, K., Akashi, K., "The preparation of ultrafine Si_3N_4 particles in a hybrid plasma"; Proceedings, 6th International Symposium on Plasma Chemistry, ISPC-6, Montréal, Québec, Canada; July 1983.

126. Kalo, A., Ozeki, T., Hojo, T., "Formation of SiC Particles from $Si(CH_3)Cl_3$ by a Plasma Gas Phase Reaction", J Less Common Met 92; 1983.

127. DePoos, O., Mollard, F., Lux, B., "Production of Beta-Silicon Carbide Ultrafine Powder by Plasma Synthesis"; Proceedings, 3rd International Symposium on Plasma Chemistry; Limoges, France; July 1977.

128. Exell, S.F., Rogger, R., Gillot, J., Lux, B., "Preparation of Ultra-Fine Powders of Refractory Carbides in an Arc-Plasma"; 2nd International Conference on Fine Particles, Boston, Mass., U.S.A.; October 7-11, 1983.

129. Heymer, G., Harnisch, M., "Verfahren und anlage zur herstellung von nitriden der elemente aluminium.bor., zilizium oder zirconium", German Patent 1,193, 489; May 30, 1963.

130. Kheidemare, G.M., Grabis, Ya. P., Miller, T.W., "High-Temperature Synthesis of Finely Dispersed Silicon Nitride"; Inorg Mater 15; 1979.

131. Samsonov, G.V., "Synthesis of Inorganic High-Melting Substances"; Plazmenye Profsessy Met. Technol. Neog. Mater.214; 1973.

132. Diana, M., Luponio, C., Russo, G., "An experimental investigation on the boron trichloride hydrogen plasma reactions at medium and high pressure", "Revue de Physique Appliquée", Vol. 12, 1977.

133. Kijima, K., "Plasma sintering of ceramic materials"; Proceedings, 7th International Symposium on Plasma Chemistry; ISPC-7; Eindhoven, The Netherlands; July 1985.

134. Burnett, J.C.: INCO Canada, Direct Communication, 1985.

135. Canadian Mines Handbook, 1984-85, (The Northern Miner).

136. Singh, S., Energy, Mines and Resources, Manitoba, Canada. Direct Communication, 1985.

APPENDIX

BASIC FINANCIAL ASSUMPTIONS, ECONOMIC CRITERIA AND UNIT PRICES

Capital Cost Estimate and Total Investment

Equipment cost and investment data received from the manufacturers, process developers and licensors were taken as a basis for estimating capital cost of the conceptual, commercial plants. (Where information and data were not available, SNC in-house data or factored cost estimates were used.) These estimates were converted and adjusted for Canadian conditions following the procedure described below.

Most of the bulk materials such as piping, fittings, concrete, etc., are assumed to be 100% Canadian. The U.S. costs were converted to Canadian prices using a material-price differential factor of 1.26 (see Table A-7). This factor was calculated by comparing Canadian and U.S. costs of similar materials.

Construction manpower and labor estimates supplied by the process developer for U.S. locations were converted using a productivity adjustment factor of 1.10. To convert from West German conditions, an adjustment factor of 1.14 was applied (Chauvel et al, IFP, Manual of Economic Analysis of Chemical Processes).

Machinery and equipment cost obtained from the U.S. were adjusted for inflation to the base month, March 1985, using the Marshall and Stevens Equipment Cost index and an exchange rate of 1.36 Canadian dollar to the U.S. dollar. For updating the U.S. cost data of the complete process unit, the Chemical Engineering Plant Index was used. For updating cost obtained from Canadian sources, the Chemical and Petroleum Plant Price Index published by Statistics Canada was used.

A typical winterization factor of 2% was applied to the total cost of each process or plant, to reflect conditions in Canada, necessitating extra insulation, heat tracing of pipes, etc.

The capital cost estimates of the processes and conceptual plants considered in this study are presented in the respective chapters. The installed-plant cost includes all the equipment items for onsite and offsite facilities, bulk materials, labour, engineering and support, and other construction costs. Contingencies of 10% for commercially proven technologies and 20% for new technologies have been included.

Start-up and miscellaneous expenses during commissioning are taken as 3% of total installed plant cost (TIPC) and it includes an allowance for additional capital for any minor modifications required to bring the plant to full design capacity, commissioning contractor fees, costs for obtaining construction permits, and construction offsite offices.

Working capital has been assumed to allow for 30-day operating supplies, chemicals, and other consumables (except water), spare parts and warehouse stock, 30-day payroll and overhead expenses, and 10-day storage of the final products.

Interest during construction is not added to the plant investment, since for calculation purposes it was assumed that the capital required for the project will be provided through 100% equity financing. The total investment cost also does not include the following:

- Gas pipeline and distribution system outside the plant site
- Electricity generation and distribution outside the plant site
- Product distribution pipeline beyond the battery limits
- Water supply and pipelines outside the plant site

- Housing, community facilities and associated infrastructure

- Roads and other transportation facilities

Annual Operating, Maintenance and Production Costs

Operating, maintenance and production costs for each process and plant are presented in the respective chapters. These costs are reported on an annual basis assuming plant operation of 8000 h/yr.

Royalties, where applicable, have been estimated using information supplied by process developers and licensors.

Operating and supervisory labor costs are calculated from manpower requirements specified by the respective process developers. Where complete information was not available, typical manpower distribution was used. For annual disbursement, average hourly rates were multiplied by a factor of 1940 h/yr.

Average hourly rates of $14/h for operating labour and $16.8/h for supervision are assumed. Manhours for supervision are assumed equal to 20% of operating labour manhours. An amount of 35% has been added to cover fringe benefits, unemployment insurance, retirement plan, etc.

Operating supplies are estimated at 30% of direct operating labor cost. Annual maintenance cost was taken as 3% of total installed plant cost (TIPC). This includes maintenance materials and supplies, equipment replacement cost, maintenance labour and supervision cost, fringe benefits, etc.

Property taxes and insurance cost are assessed at 2.25% of TIPC. Plant overhead and administration is assumed to be 35% of direct labour cost, operating supplies and maintenance. It includes plant management, engineering, fire protection, medical services and personnel, accounting, purchasing, clerical and janitorial services.

To calculate final product cost, financial analyses were made in "constant" dollars, assuming 100% equity financing. A straight line depreciation was applied over a plant life of 20 years. At the end of the project, a plant salvage value of zero was assumed. Land and working capital were assumed to be fully recovered. Product cost was calculated to achieve a 9% return on equity (ROE)* before taxes in "real" terms.

The basic financial assumptions and economic criteria accepted in this study are presented in Table A-1. Unit prices of materials and energy as well as labour costs for different processes and plant locations considered are shown in Tables A-2 to A-6. Electricity costs vary from region to region and depend on the power consumed. For the cases investigated in this study, the following rates were assumed.

	Québec	Alberta
< 5 MW	3¢/kWh	-
> 40 MW	2.4¢/kWh	3¢/kWh

By-product credits have been taken using the values shown in Tables A-4, A-5, and A-6.

All costs are presented in constant Canadian dollars, March 1985.

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* Return on equity (ROE) is expressed in "real" terms, i.e., current rate minus inflation (15% - 6% = 9% before tax).

Table A-1 Basic Financial Assumptions and Economic Criteria

Constant Canadian dollars*	: March 1985			
Capital investment schedule**				
		Construction Period		
		2 years %	3 years %	
	year	1 40	1 22	
		2 60	2 48	
		-	3 30	
		100	100	
Project and estimating contingency**	: 10% for commercially proven technologies 20% for novel technologies			
Financing	: 100% equity			
Return on equity	: 9% before taxes in "real" terms			
Tax rate	: 45%			
Investment tax credit	: neglected			
Plant operating efficiency**				
	Year %			
	1 90			
	2-20 100			
Plant life	: 20 years			
Depreciation method	: straight line			
Salvage value	: zero			
Plant operation	: 8000 h/yr			

* In "constant" dollar analysis, return on equity is expressed in "real" terms, i.e., current rates minus inflation (15% - 6% = 9%)
Average inflation of 6% per annum over 20 years is assumed.

** For cases where conceptual plant design is considered.

Table A-2 Unit Prices of Materials and Energy, and Labour Cost for Iron and Steel Production (Canadian dollars, March 1985)

Ferrous Materials	
Oxide pellets	$75/t
Ore concentrates	$28/t
Alloys	$600/t
Revert scrap	$110/t
Scrap (credit)	$110/t
Dust and Sludge (credit)	$69/t
Fuel	
Coke	$138/t
Coking coal	$83/t
Carbon additive	$0.2/kg
Low-S non-metallurgical coal	$72/t
Fuel (Natural Gas)	$3.783/GJ
Fuel (credit)	$3.783/GJ
Electricity	$0.024/kWh
Electricity (credit)	$0.024/kWh
Other Materials	
CaC_2	$0.450/kg
Oxygen	$0.07/$m^3$
Electrode (graphite)	$3/kg
Electrode (self-baking)	$0.45/kg
Limestone	$13/t
Flux	$75/t
Lime	$82/t
Spar	$180/t
Labour and Supervision	
Operating labour	$14/h plus 35% fringe benefits
Supervision	$16.8/h plus 35% fringe benefits

Table A-3 Unit Prices of Materials and Energy, and Labour Cost For Ferromolybdenum Production (Canadian dollars, March 1985)

Mo in molybdenite concentrates	$10.7/kg	($4.84/lb)
Natural Gas Cost	$3.783/GJ	($40/$10^6$ Btu)
Electricity	$0.03/kWh	(3¢/kWh)
Scrap Steel	$110/t	
Mill Scale	$60/t	
Fluorspar Flux	$210/t	
Lime Flux	$75/t	
Limestone	$13/t	
Silica Sand	$35/t	
Nitrogen	11.2¢/Nm^3	(30¢/100 scf)
Make-up water	$0.132/$m^3$	($0.5/1000 US gal)
Labour and Supervision		
Operating labour	$14/h plus 35% fringe benefits	
Supervision	$16.8/h plus 35% fringe benefits	
By-product Credits		
Sulphur	$65/t	

Table A-4 Unit Prices of Materials and Energy, and Labour Cost for Natural Gas Plasma Processing to Acetylene and other Hydrocarbons in Québec (Canadian dollars, March 1985)

PLANT LOCATION	QUÉBEC	
Natural Gas	$3.783/GJ	($4/$10^6$ Btu)
Electricity	$0.024/kWh	(2.4¢/kWh)
LPG	$166/$m^3$	(16.6¢/L)
Chemicals and Solvents		
Hydrocarbon	$189/t	($30/bbl)
Methanol	$0.2685/kg	($268.5/t)
Hydrocarbon Solvent	$520/t	(40¢/L)
Make-up water	$0.132/$m^3$	($0.5/1000 US gal)
Labour and Supervision		
Operating Labour	$14/h plus 35% fringe benefits	
Supervision	$16.8/h plus 35% fringe benefits	
By-products Credits		
Ethylene	$0.44/kg	(20¢/lb)
Hydrogen	$4.74/GJ $7.58/GJ	($5/$10^6$ Btu) and ($8/$10^6$ Btu)
Propylene/Butylene	$420/t	(19¢/lb)
Benzene	$539/t	(47¢/L)

Table A-5 Unit Prices of Materials and Energy, and Labour Cost for Natural Gas Plasma Processing to Acetylene and other Hydrocarbons in Alberta (Canadian dollars, March 1985)

PLANT LOCATION	ALBERTA	
Natural Gas	$2.798/GJ	($2.95/$10^6$ Btu)
Electricity	$0.03/kWh	(3¢/kWh)
LPG	$133/$m^3$	(13.3¢/l)
Chemicals and Solvents		
Hydrocarbon	$189/t	($30/bbl)
Methanol	$0.2685/kg	($268.5/t)
Hydrocarbon Solvent	$520/t	(40¢/L)
Make-up water	$0.132/$m^3$	($0.5/1000 US gal)
Labour and Supervision		
Operating Labour	$14.5/h plus 35% fringe benefits	
Supervision	$17.4/h plus 35% fringe benefits	
By-products Credits		
Ethylene	$0.4/kg	(18¢/lb)
Hydrogen	$4.27/GJ $6.83/GJ	($4.5/$10^6$ Btu) and ($7.2/$10^6$ Btu)
Propylene/Butylene	$378/t	(17¢/lb)
Benzene	$485/t	(42.3¢/L)

Table A-6 Unit Prices of Materials and Energy, and Labour Cost for Plasma Processing of Coal to Acetylene (AVCO Process) in Alberta (Canadian dollars, March 1985)

PLANT LOCATION	ALBERTA	
Coal	: $35/t	
Electricity	: $0.03/kWh	(3¢/kWh)
LPG	: $133/$m^3$	(13.3¢/L)
Nitrogen	: 11.2¢/Nm^3	(30¢/100 scf)
Make-up water	: $0.132/$m^3$	($0.5/1000 US gal)
Labour and Supervision		
Operating Labour	: $14.5/h plus 35% fringe benefits	
Supervision	: $17.4/h plus 35% fringe benefits	
By-products Credits		
Char and Carbon Black	: $35/t	
HCN	: $1.1/kg	
CS_2	: $0.463/kg	
Ethylene	: $0.4/kg	(18¢/lb)

Table A-7 Canada/USA Material Price Differential Factor
[Reference Location: Gulf Coast (USA)]

	Relative Price*	Material** Distribution %	
Concrete Mix	1.37	30	0.411
Standard Structure			
Wide Flanges	1.27	7.5	0.095
I-Beams	1.21	7.5	0.095
Piping			
Iron	1.2	36.0	0.432
Copper	1.3	9.0	0.117
Cables/Wires	1.10	10.0	0.11
		100.0	1.26

Sources:

* Engineering New Record, June 4, 1984;
** Based on SNC in-house date on various petrochemical projects.